2023 NFPA TECHNOLOGY ROADMAP

IMPROVING THE DESIGN, MANUFACTURE AND FUNCTION OF FLUID POWER COMPONENTS AND SYSTEMS

TABLE OF CONTENTS

BACKGROUND AND INTRODUCTION

Technology Roadmap for the Fluid Power Industry

In August 2009, the National Fluid Power Association (NFPA) published the *Technology Roadmap for the Fluid Power Industry.* The purpose of the Roadmap was to provide NFPA member companies and their research partners with an industry-wide consensus regarding the research and development needs of the fluid power industry.

The Roadmap was the result of a facilitated process among representatives from 20 organizations in the fluid power industry, and it charted a ten-year research and technology development agenda to realize industry-elevating advancements in mobile hydraulics, industrial hydraulics, and pneumatics. In creating the Roadmap, the representatives specifically focused on advancements they thought would help the industry meet the future needs of its customers, expand fluid power into new customer markets, and attract the best and brightest students to the field.

After its publication, this Roadmap was used by the NFPA Education and Technology Foundation and the Center for Compact and Efficient Fluid Power (CCEFP) to guide their respective research efforts, and by numerous NFPA members and other industry partners to inform decisions about research partnerships and product development.

A Pre-Competitive Research Agenda for the Fluid Power Industry

In 2012, NFPA convened a task force of industry representatives to review and update the *Technology Roadmap for the Fluid Power Industry*. Their report, *A Pre-Competitive Research Agenda for the Fluid Power Industry*, was published in January 2013, and addressed several shortcomings of the original Roadmap. The updated report:

- Expanded the use of end market customer perspectives and drivers in determining the fluid power research challenges to be met and objectives to be achieved.
- Defined “pre-competitive” for the purposes of the report and NFPA’s future use. The report’s research agenda is targeted in areas that are broad enough that they are unlikely to be pursued by individual companies for competitive advantage but targeted enough that they are likely to result in technological advancements that can assist wide industry sectors.
- Reviewed and incorporated the research successes and progress of the CCEFP in the identification of future research objectives.
- Made specific recommendations for supporting market education and standardization efforts that will complement and help advance the research agenda.

The 2012 report was again used by the NFPA Education and Technology Foundation and the CCEFP to guide their respective research efforts, and again by numerous NFPA members and other industry partners to inform decisions about research partnerships and product development. It was also used by NFPA to guide its market education and standards development work.

NFPA Roadmap Committee

In 2014, NFPA launched the NFPA Roadmap Committee, a volunteer structure tasked with developing, maintaining, and supplementing the NFPA Technology Roadmap, the industry consensus-based document which identifies the areas of pre-competitive research needed to increase fluid power's competitive position in the marketplace, open new markets for fluid power, and attract the best and brightest students to the field.

The Committee published its first report in August 2015. It was an update to the task force report published in January 2013, reviewing and updating a pre-competitive research agenda for the fluid power industry. Because many of the challenges addressed in that agenda dealt with the design and function of fluid power components and systems, the report was titled the *2015 NFPA Technology Roadmap: Improving the Design and Function of Fluid Power Components and Systems.*

In completing that work, the Committee utilized many of the same processes and objectives identified by the 2012 task force, including the use of end market customer perspectives and drivers, the definition of pre-competitive research, the incorporation of CCEFP research successes and progress, and the inclusion of market education and standardization recommendations.

The Committee now repeats this function on a biennial basis, updating the Roadmap as needed to reflect the evolving needs of fluid power component and system manufacturers and their customers. It published its first updated Roadmap in August 2017.

Fluid Power Advanced Manufacturing Consortium (FPAMC)

The FPAMC was established in 2015 through a federal grant from the National Institute of Standards and Technology (NIST). Administered by the CCEFP, the purpose of the FPAMC was threefold: (1) Identify the key enabling manufacturing technologies necessary to improve the manufacture and function of fluid power components; (2) Transcribe the research necessary to improve these technologies for fluid power's use onto manufacturing roadmaps; and (3) Establish a sustaining, interdisciplinary consortium focused on creating, maintaining, expanding and facilitating implementation of these advanced manufacturing roadmaps for the U.S. fluid power industry.

The FPAMC published its first report in May 2017, which focused on enabling the fluid power industry's use of coatings, micromachining, composites and engineered plastics, sintered metals, additive manufacturing, batch-free heat treating, robotics, hybrid manufacturing, metrology, and in-process sensing, feedback and control.

The 2017 NFPA Technology Roadmap incorporated some of these elements, but the two reports – the 2017 NFPA Technology Roadmap focused on the design and function of fluid power components and systems and the 2017 FPAMC "Manufacturing Roadmap" focused on the manufacture of fluid power components – are best viewed as separate documents with distinct purposes.

2019 NFPA Technology Roadmap

In the third publication of the NFPA Roadmap Committee, published in August 2019, an attempt was made to combine the findings of the two 2017 roadmaps into one comprehensive report. As such, the report was titled the *2019 NFPA Technology Roadmap: Improving the Design, Manufacture and Function of Fluid Power Components and Systems.*

2021 NFPA Technology Roadmap

In the fourth publication of the NFPA Roadmap Committee, published in August 2021, the focus remained on improving the design, manufacture and function of fluid power components and systems.

In its preparation, the NFPA Roadmap Committee was expanded to include a wider diversity of stakeholders across the fluid power supply chain, and several surveys of stakeholders in the broader fluid power customer and motion control industries were utilized to better inform the discussions and decisions of the Committee.

2023 NFPA Technology Roadmap

In this, the fifth publication of the NFPA Roadmap Committee, both the focus on the design, manufacture and function of fluid power components and systems, and the expanded engagement with stakeholder across the fluid power and motion control supply chain, have been maintained.

The Committee worked via email, conference call, and virtual meeting from December 2022 to July 2023 to complete this report. Although the report contains information regarding the consensus and individual opinions of the Committee members, and represents their most up-to-date thinking on the state-of-the-art, the report should not be interpreted as the single or wholly comprehensive agenda for the fluid power industry.

The 2023 NFPA Technology Roadmap is a tool that can be used, with permission obtained from NFPA, by organizations that wish to pursue projects of importance to the fluid power industry. These organizations include both research institutions and companies across the fluid power supply chain. By aligning their activities with the challenges, objectives, and proposed projects described in the Roadmap, they will all play a role in positively shaping the future of fluid power technology.

NFPA will continue to use the Roadmap to shape and direct the research efforts of the NFPA Education & Technology Foundation, the CCEFP, and a growing marketplace of academic and industry researchers. It will also use the Roadmap as a vehicle by which to attract and organize additional funding for the projects and initiatives it describes.

By putting forth this Roadmap, representing a broad consensus of industry players, and focused on pre-competitive initiatives that will help develop new technologies to benefit the industries, markets, and people served by fluid power, NFPA demonstrates a commitment both to collaboration and to long-term growth and sustainability.

ROADMAP ELEMENTS

The 2023 NFPA 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.

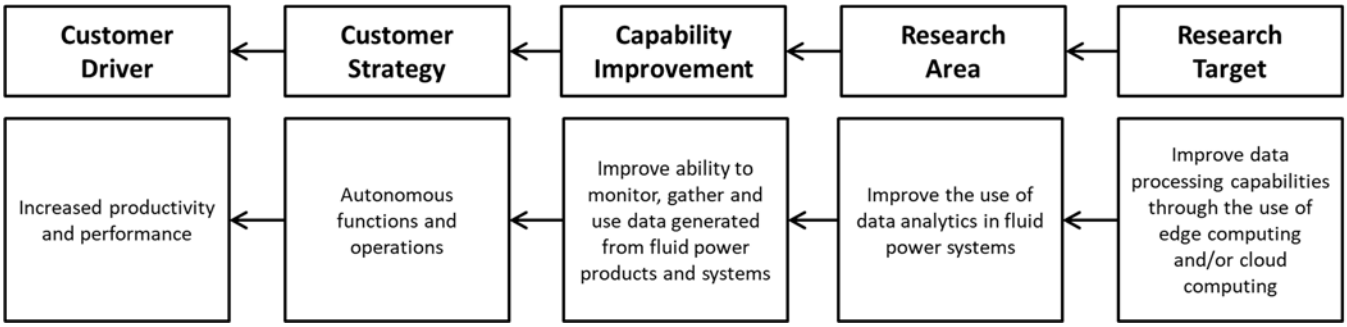
2. **Customer Strategies** are the machine-level objectives and technologies that the machine builders have set or are using to help them achieve the top-level performance objectives described by the Customer Drivers. Again, these Customer Strategies are not necessarily connected to their use of fluid 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:



ROADMAP UPDATE PROCESS AND TIMELINE

The following process and timeline were used to update the NFPA Technology Roadmap and produce this report.

	Phase 1 – Customer Drivers and Strategies
Dec 1, 2022	Present Roadmap process and timeline
	Launch of survey on Customer Drivers and Strategies
Dec 22, 2022	Deadline to respond to survey on Customer Drivers Strategies
Jan 12, 2023	Virtual committee meeting to discuss, define and prioritize Customer Drivers and Strategies
	Phase 2 – Capability Improvements
Jan 26, 2023	Meeting report sent with prioritized Customer Drivers and Strategies and setting the stage for fluid power alignment and Capability Improvements
	Launch of survey on fluid power alignment and Capability Improvements
Feb 16, 2023	Deadline to respond to survey on fluid power alignment and Capability Improvements
Mar 2, 2023	Virtual committee meeting to discuss, define and prioritize Capability Improvements
	Phase 3 – Research Areas and Targets
Mar 16, 2023	Meeting report sent with prioritized Capability Improvements and setting the stage for Research Areas and Targets, including process for defining working groups for each Capability Improvement
	Launch of survey on Research Areas and Targets
Apr 6, 2023	Deadline to respond to survey on Research Areas and Targets
Apr/May 2023	Virtual working group meetings to discuss and prioritize Research Areas and Targets for each Capability Improvement
Jun 1, 2023	Virtual committee meeting to review and harmonize Research Areas and Targets for each Capability Improvement

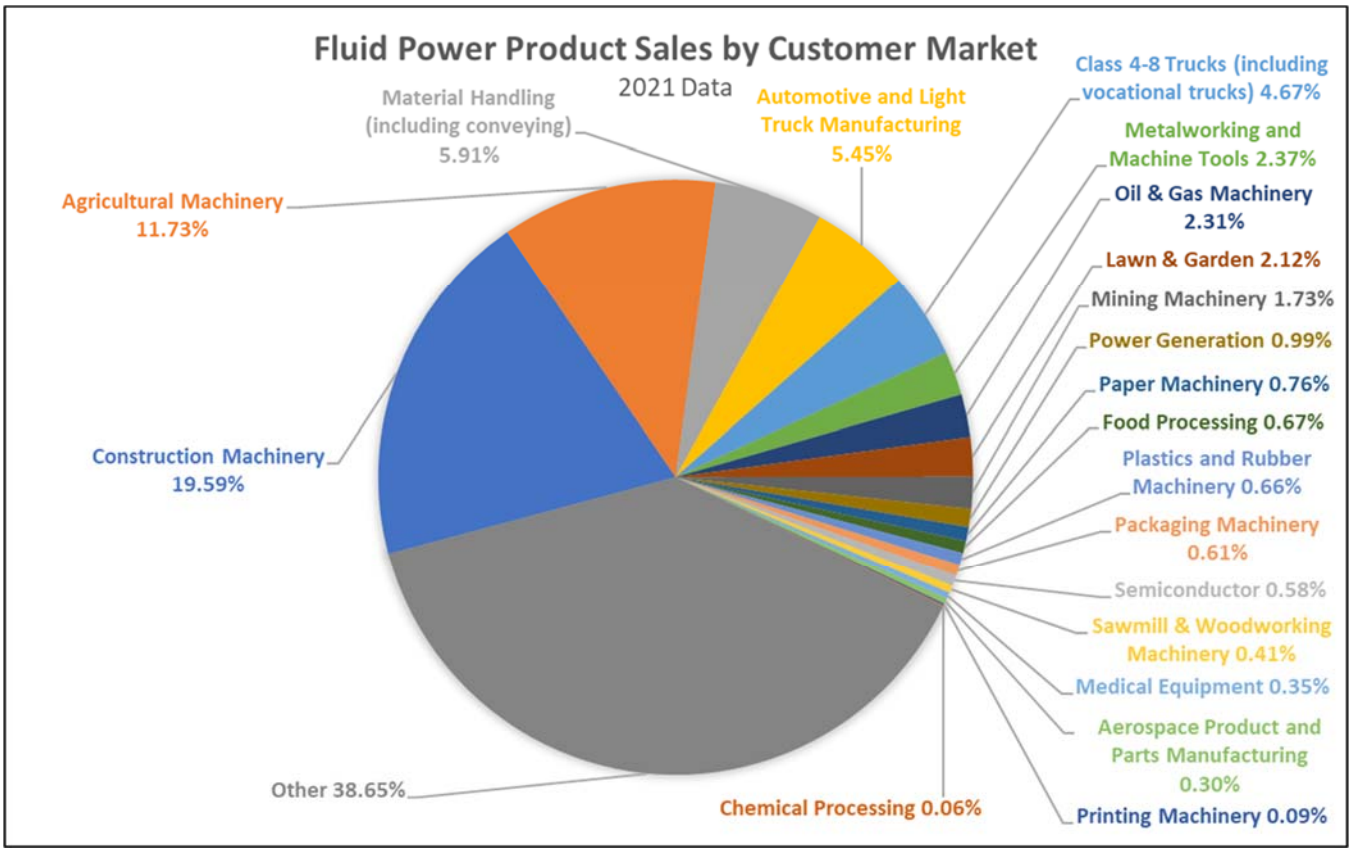
Phase 4 – Final Roadmap Document

Jun 2023	Draft Roadmap document written
Jun 29, 2023	Draft Roadmap document sent for review and comment
Jul 13, 2023	Deadline to return comments on draft Roadmap
Aug 15, 2023	Final Roadmap document published and presented at NFPA Industry and Economic Outlook Conference

CUSTOMER MARKETS

Fluid power technology is used in hundreds of applications in dozens of specific customer markets. Generally speaking, all of fluid power's customer markets can be grouped into two general areas: those that are served by hydraulics and those that are served by pneumatics.

According to NFPA's latest data, the 20 largest customer markets represent nearly 62% of all hydraulic and pneumatic product sales.



When referencing customers and their needs, the 2023 NFPA Technology Roadmap therefore defaults to customers in these 20 markets, namely:

- Construction Machinery
- Agricultural Machinery
- Material Handling (including conveying) Equipment
- Automotive and Light Truck Manufacturing
- Class 4-8 Trucks (including vocational trucks)
- Metalworking and Machine Tools
- Oil and Gas Machinery
- Lawn and Garden Equipment

- Mining Machinery
- Power Generation Equipment
- Paper Machinery
- Food Processing Machinery
- Plastics and Rubber Machinery
- Packaging Machinery
- Semiconductor Manufacturing Machinery
- Sawmill and Woodworking Machinery
- Medical Equipment
- Aerospace Products and Parts Manufacturing
- Printing Machinery
- Chemical Processing Equipment

The large segment shown as “Other” is an artifact on how this data is collected, with some responders unable to break their sales into discrete customer markets.

CUSTOMER DRIVERS AND STRATEGIES

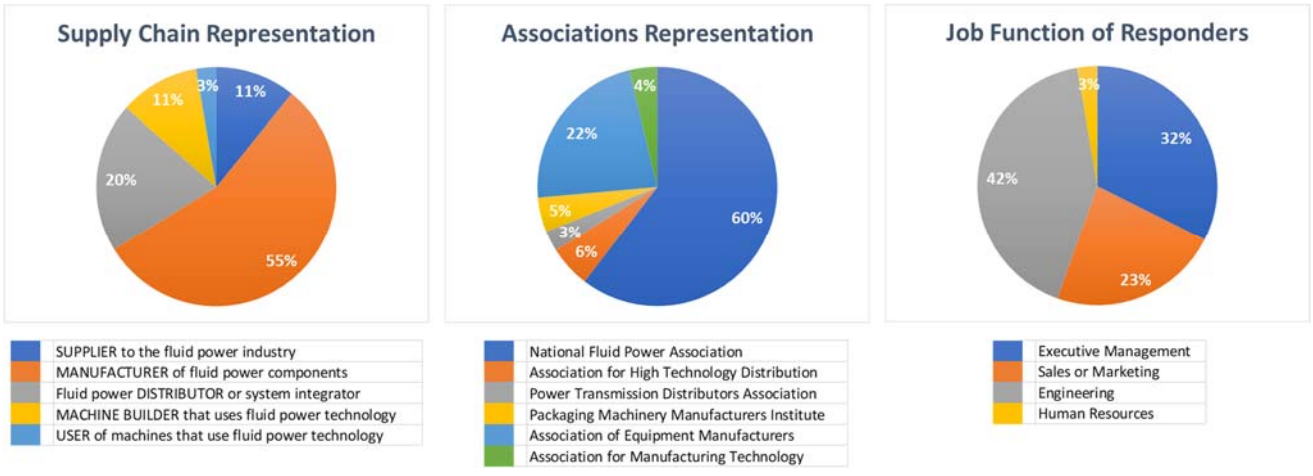
Customer Drivers are the top-level performance objectives of fluid power customers, the OEMs or machine builders that manufacture machines that often incorporate fluid power systems. Customer Drivers help these machine builders serve the needs of their own customers and are not necessarily connected to their use of fluid power.

In the 2021 NFPA Technology Roadmap, the following seven Customer Drivers were identified as those of highest importance to the majority of fluid power customer markets:

- **Increased availability and up-time**
- **Increased productivity and performance**, including through efforts to provide autonomous functions and operations, and to use of integrated data and intelligence
- **On-time delivery of the machine**, including through efforts to decrease lead time in getting the machine
- **Lower capital and operating costs**
- **Compliance with environmental and safety regulations and machine directives**
- **Easier and more predictable maintenance**, including through efforts to use integrated data and intelligence
- **Increased energy efficiency**, including through efforts to reduce weight and increase power density

<u>Survey on Drivers in Fluid Power Customer Markets</u>

NFPA conducted a survey in December 2022 to assist in determining the current importance of these Customer Drivers in the 20 largest fluid power customer markets, and in determining if any new Drivers had emerged in these markets since the time of the 2021 NFPA Technology Roadmap. The survey received responses from 74 individuals across the fluid power supply chain, including a large percentage from members of the NFPA Roadmap Committee.



Importance of Existing Customer Drivers

Respondents were asked to rank the importance of each Customer Driver in each of the customer markets with which they were familiar. Some variations in importance emerged for particular markets. In the aggregate, all the drivers were ranked as at least somewhat important, with "Increased availability and up-time" ranked highest and "Increased energy efficiency" ranked lowest.

		CUSTOMER DRIVERS						
CUSTOMER MARKETS	N	Increased availability and up-time	Increased productivity and performance	On-time delivery of the machine	Lower capital and operating costs	Compliance with environmental and safety regulations and machine directives	Easier and more predictable maintenance	Increased energy efficiency
Aerospace Product and Parts Manufacturing	13	4.000	3.769	4.000	3.615	4.231	3.692	3.615
Agricultural Machinery	50	4.520	4.240	4.040	3.940	3.800	3.760	3.860
Automotive and Light Truck Manufacturing	11	4.455	4.364	3.909	4.091	4.000	3.636	3.727
Chemical Processing Machinery	2	4.500	4.000	3.000	4.500	3.500	4.000	3.500
Class 4-8 Trucks (including vocational trucks)	8	4.375	4.000	3.625	3.750	3.500	3.750	3.500
Construction Machinery	37	4.622	4.459	3.730	4.108	3.892	3.892	3.892
Food Processing Equipment	12	4.583	4.083	4.083	4.000	4.417	4.000	3.333
Lawn and Garden Equipment	13	3.923	3.923	3.769	4.000	3.692	3.462	3.462
Material Handling (including conveying) Equipment	26	4.577	4.385	3.808	4.192	3.731	3.692	3.923
Medical Equipment	8	4.250	4.500	3.375	3.250	4.625	3.750	3.000
Metalworking Machinery and Machine Tools	15	4.467	4.400	4.000	4.133	3.267	3.867	3.667
Mining Machinery	19	4.632	4.368	3.684	3.789	4.158	4.263	3.789
Oil and Gas Machinery	10	4.600	4.400	3.700	4.100	4.200	3.900	3.500
Packaging Machinery	10	4.600	4.600	4.000	3.900	3.500	4.100	3.400
Paper Machinery	6	4.833	5.000	3.833	4.500	3.667	4.167	4.167
Plastics and Rubber Machinery	4	4.250	4.750	3.250	3.750	3.250	4.000	3.000
Power Generation Equipment	2	5.000	5.000	4.000	4.500	5.000	4.500	4.000
Printing Machinery	3	4.333	4.333	4.000	4.000	4.000	3.667	3.667
Sawmill and Woodworking Machinery	7	4.571	4.571	3.857	4.286	3.429	3.857	3.714
Semiconductor Machinery	6	4.667	4.333	4.167	3.500	3.500	4.167	3.333
All Responses	262	4.492	4.324	3.851	3.981	3.855	3.851	3.698

5	Extremely important
4	Very important
3	Somewhat important
2	Not so important
1	Not at all important
	5.000 - 4.500
	4.499 - 4.000
	3.999 - 3.500
	3.499 - 3.000
	2.999 - 2.500
	2.499 - 2.000

Most Important Customer Driver

Respondents were also asked to identify the most important Customer Driver in each of the customer markets with which they were familiar. Some variations emerged for particular markets, but in the aggregate, the overwhelming choice was for "Increased productivity and performance" and "Increased availability and up-time."

		CUSTOMER DRIVERS						
CUSTOMER MARKETS	N	Increased availability and up-time	Increased productivity and performance	On-time delivery of the machine	Lower capital and operating costs	Compliance with environmental and safety regulations and machine directives	Easier and more predictable maintenance	Increased energy efficiency
Aerospace Product and Parts Manufacturing	12	17%	25%	17%	8%	33%	0%	0%
Agricultural Machinery	49	33%	35%	12%	6%	6%	0%	8%
Automotive and Light Truck Manufacturing	11	9%	27%	9%	18%	18%	9%	9%
Chemical Processing Machinery	2	50%	0%	0%	0%	0%	0%	50%
Class 4-8 Trucks (including vocational trucks)	8	38%	0%	13%	13%	25%	13%	0%
Construction Machinery	37	22%	46%	5%	8%	8%	3%	8%
Food Processing Equipment	12	17%	33%	8%	0%	33%	0%	8%
Lawn and Garden Equipment	13	23%	0%	0%	54%	15%	8%	0%
Material Handling (including conveying) Equipment	26	42%	19%	12%	19%	0%	0%	8%
Medical Equipment	7	29%	29%	0%	0%	43%	0%	0%
Metalworking Machinery and Machine Tools	15	20%	53%	7%	13%	7%	0%	0%
Mining Machinery	19	37%	16%	0%	16%	11%	21%	0%
Oil and Gas Machinery	10	70%	10%	0%	10%	10%	0%	0%
Packaging Machinery	10	10%	60%	10%	10%	0%	10%	0%
Paper Machinery	6	33%	50%	0%	0%	17%	0%	0%
Plastics and Rubber Machinery	4	50%	50%	0%	0%	0%	0%	0%
Power Generation Equipment	2	50%	0%	0%	0%	50%	0%	0%
Printing Machinery	2	0%	50%	50%	0%	0%	0%	0%
Sawmill and Woodworking Machinery	7	14%	57%	0%	14%	0%	14%	0%
Semiconductor Machinery	6	50%	33%	0%	0%	0%	0%	17%
All Responses	258	29%	31%	7%	12%	11%	4%	5%

	Highest ranked
	Second highest ranked

Customer Drivers – Hydraulic vs. Pneumatic Markets

When comparing responses for the top 5 hydraulic markets to the top 5 pneumatic markets, not much variation emerges – either from each other or from the aggregate of all responses. For both, the two most important drivers are "Increased availability and up-time" and "Increased productivity and performance." The biggest variations are "Increased energy efficiency," which scored on average 0.329 higher for hydraulic markets than for pneumatic markets, and "Easier and more predictable maintenance," which scored on average 0.153 higher for pneumatic markets than for hydraulic markets.

		CUSTOMER DRIVERS						
CUSTOMER MARKETS	N	Increased availability and up-time	Increased productivity and performance	On-time delivery of the machine	Lower capital and operating costs	Compliance with environmental and safety regulations and machine directives	Easier and more predictable maintenance	Increased energy efficiency
Construction Machinery	37	4.622	4.459	3.730	4.108	3.892	3.892	3.892
Agricultural Machinery	50	4.520	4.240	4.040	3.940	3.800	3.760	3.860
Material Handling (including conveying) Equipment	26	4.577	4.385	3.808	4.192	3.731	3.692	3.923
Class 4-8 Trucks (including vocational trucks)	8	4.375	4.000	3.625	3.750	3.500	3.750	3.500
Automotive and Light Truck Manufacturing	11	4.455	4.364	3.909	4.091	4.000	3.636	3.727
TOP 5 HYDRAULIC MARKETS	132	4.545	4.326	3.871	4.038	3.811	3.773	3.848
Automotive and Light Truck Manufacturing	11	4.455	4.364	3.909	4.091	4.000	3.636	3.727
Food Processing Equipment	12	4.583	4.083	4.083	4.000	4.417	4.000	3.333
Packaging Machinery	10	4.600	4.600	4.000	3.900	3.500	4.100	3.400
Semiconductor Machinery	6	4.667	4.333	4.167	3.500	3.500	4.167	3.333
Metalworking Machinery and Machine Tools	15	4.467	4.400	4.000	4.133	3.267	3.867	3.667
TOP 5 PNEUMATIC MARKETS	54	4.537	4.352	4.019	3.981	3.741	3.926	3.519
All Responses	262	4.492	4.324	3.851	3.981	3.855	3.851	3.698

5	Extremely important
4	Very important
3	Somewhat important
2	Not so important
1	Not at all important
	5.000 - 4.500
	4.499 - 4.000
	3.999 - 3.500
	3.499 - 3.000
	2.999 - 2.500
	2.499 - 2.000

Suggestions for New Customer Drivers

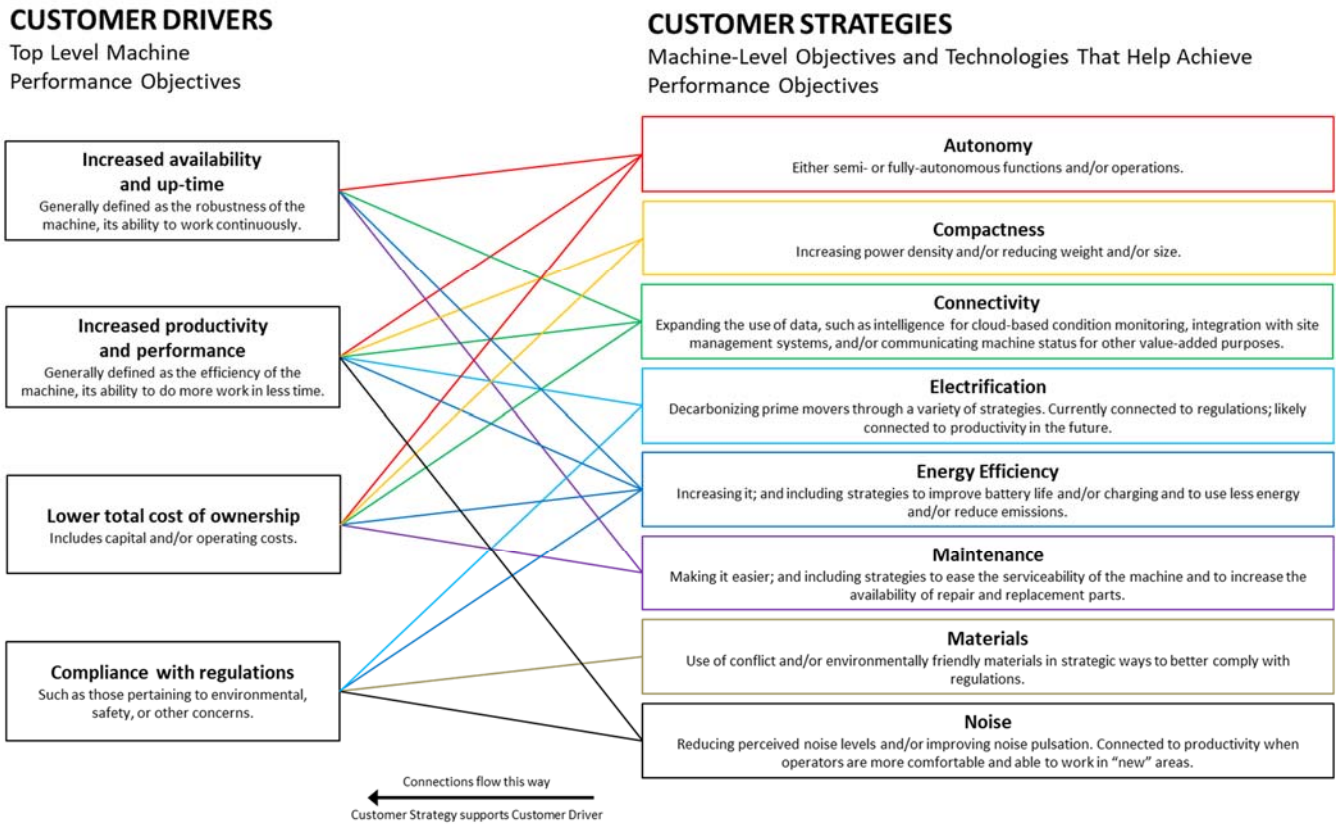
Survey responders also provided suggestions for new Customer Drivers that had emerged since the time of the 2021 NFPA Technology Roadmap. These suggestions included:

- Autonomous operation and capabilities (robotic or otherwise)
- Cloud based condition monitoring
- Communicating status of machine
- Compact size of machinery
- Conflict or strategic material usage
- Ease of serviceability
- Electrification (i.e., increase in the use of electric power sources that serve as the prime mover in either the propulsion circuit, work circuit, or both)
- Environment friendly fluids
- Integration with site management systems
- Noise levels
- Quality

- Repair/replacement parts availability
- Simple systems

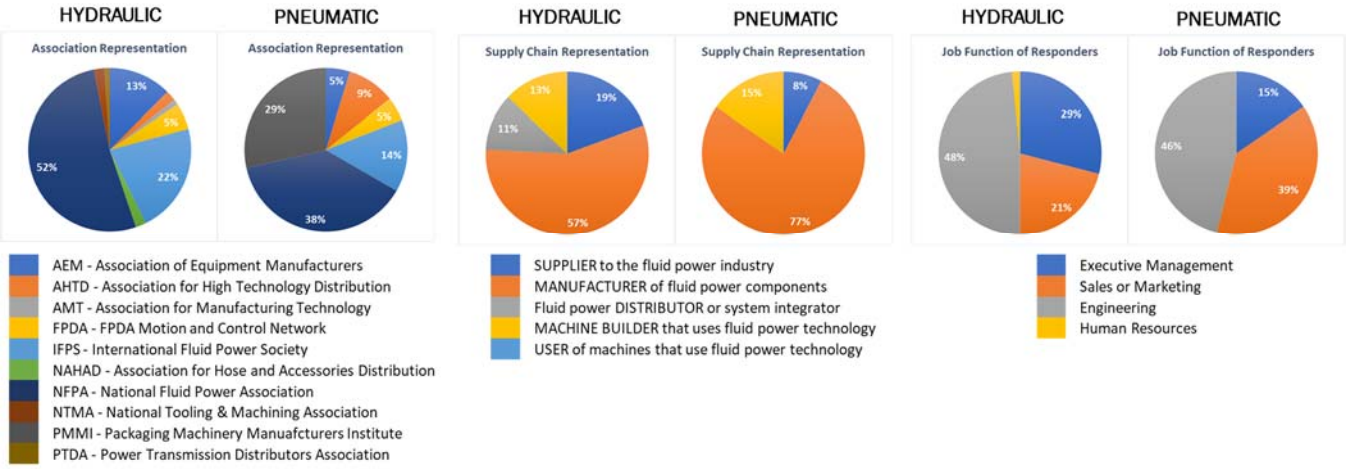
Identification of Customer Drivers and Strategies for the 2023 NFPA Roadmap

The survey data on existing Drivers and the suggestions for new Drivers were reviewed by the NFPA Roadmap Committee at its January 12, 2023 meeting. In discussing which Customer Drivers to prioritize for the 2023 Roadmap, the Committee first decided to make a distinction between Customer Drivers (the top level machine performance objectives) and Customer Strategies (machine-level objectives and technologies that help achieve one or more of the performance objectives). With that distinction in mind, the Committee proceeded to discuss each item in turn, and determined which items would be positioned as Customer Drivers, which items would be positioned as Customer Strategies, how each should be listed and defined, and how each Customer Strategy was connected to which Customer Drivers. The outcomes of that discussion are shown below.



FLUID POWER'S ALIGNMENT WITH CUSTOMER STRATEGIES

NFPA conducted two surveys in February 2023 to assist in determining fluid power's current ability to meet the needs represented by the Customer Strategies. One survey asked about the current capabilities of hydraulics; the other about the current capabilities of pneumatics. Together, the surveys received responses from 75 individuals across the fluid power supply chain, including a large percentage from the members of the NFPA Roadmap Committee.



Survey participants were asked how important each of the Customer Strategies were to the technology and performance objectives of the machine builders in their marketplace, and they were asked how frequently hydraulics or pneumatics were included as part of each strategy. The scoring scale was: 5 = Extremely important or Always; 4 = Very important or Usually; 3 = Somewhat important or Sometimes; 2 = Not so important or Rarely; 1 = Not at all important or Never.

		HYDRAULICS		
CUSTOMER STRATEGIES	N	IMPORTANCE	FREQUENCY	GAP
Autonomy	55	3.709	3.473	-0.236
Compactness	50	3.720	3.780	0.060
Connectivity	47	3.979	3.511	-0.468
Electrification	44	4.000	3.614	-0.386
Energy Efficiency	43	3.884	3.767	-0.116
Maintenance	43	3.977	3.907	-0.070
Materials	43	3.326	3.349	0.023
Noise	43	3.721	3.698	-0.023
All Responses	368	3.788	3.633	-0.155

3.9 or greater / 3.7 to 3.9 / Below 3.7 — 3.9 or greater / 3.7 to 3.9 / Below 3.7 — 0 or greater / 0 to -0.25 / Below -0.25

		PNEUMATICS		
CUSTOMER STRATEGIES	N	IMPORTANCE	FREQUENCY	GAP
Autonomy	9	3.444	3.222	-0.222
Compactness	9	3.556	3.222	-0.333
Connectivity	8	3.750	3.500	-0.250
Electrification	8	3.625	3.250	-0.375
Energy Efficiency	8	3.250	3.000	-0.250
Maintenance	8	4.125	4.125	0.000
Materials	8	3.500	3.250	-0.250
Noise	8	3.500	3.250	-0.250
All Responses	66	3.591	3.348	-0.242

3.9 or greater / 3.7 to 3.9 / Below 3.7 — 3.9 or greater / 3.7 to 3.9 / Below 3.7 — 0 or greater / 0 to -0.25 / Below -0.25

Generally speaking, the Customer Strategies were rated as more important in the hydraulic marketplace, and hydraulics was seen as better aligned with them.

For hydraulics, the two positive gaps between importance and frequency were in Compactness and Materials, suggesting that hydraulics is already well aligned with these Customer Strategies. The two largest negative gaps were in Connectivity and Electrification, suggesting that these may be key areas of focus for the development of new hydraulic technologies.

For pneumatics, the only non-negative gap between importance and frequency was in Maintenance, suggesting that pneumatics is already well aligned with this Customer Strategy. The two largest negative gaps were in Electrification and Compactness, suggesting that these may be key areas of focus for the development of new pneumatic technologies.

CAPABILITY IMPROVEMENTS

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.

In the 2021 NFPA Technology Roadmap, the following seven Capability Improvements were identified as those of highest importance for the fluid power industry to pursue in order to meet or better meet these customer needs.

- Improve fluid power control systems (including through electrification)
- Monitor, gather and use data generated from working fluid power products to add value
- Improve fluid power's reliability and durability
- Increase fluid power's energy efficiency
- Increase fluid power's power density
- Reduce the environmental impact of fluid power components and systems
- Reduce lead time for fluid power components and their control elements

<u>Importance of Existing Capability Improvements</u>

In the two surveys NFPA conducted in February 2023, respondents were also asked to assess the importance of these Capability Improvements in helping fluid power meet the needs described by the final Customer Strategies.

Participants in the hydraulic survey were asked to rank how important each of the 2021 Capability Improvements would be in increasing the use of hydraulics in each Customer Strategy. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		CAPABILITY IMPROVEMENTS						
CUSTOMER STRATEGIES	N	Improving hydraulic control systems	Improving ability to monitor, gather, and use data generated from hydraulic products and/or systems	Improving the reliability and/or durability of hydraulic products and/or systems	Increasing the energy efficiency of hydraulic products and/or systems	Increasing the power density of hydraulic products and/or systems	Reducing the environmental impact of hydraulic products and/or systems	Reducing the lead time for hydraulic products and their control elements
Autonomy	54	4.074	4.204	3.907	3.667	3.407	3.185	3.519
Compactness	48	3.667	3.542	3.833	4.104	4.188	3.167	3.396
Connectivity	46	3.978	4.522	3.826	3.478	3.043	3.065	3.283
Electrification	43	4.023	4.047	3.651	4.116	3.581	3.256	3.302
Energy Efficiency	42	4.119	4.071	3.667	4.476	3.833	3.333	3.286
Maintenance	42	3.571	4.357	4.524	3.262	3.024	3.143	3.452
Materials	41	2.927	2.902	3.707	3.244	3.244	3.488	3.146
Noise	42	3.738	3.429	3.524	3.571	3.333	3.262	2.976
All Responses	358	3.777	3.899	3.832	3.743	3.464	3.232	3.304

5.000 - 4.500
4.499 - 4.000
3.999 - 3.500
3.499 - 3.000
2.999 - 2.500
2.499 - 2.000

These results show the three capability improvements with the greatest potential impact on the use of hydraulics are improving the use of data, improving reliability/durability, and improving control systems.

Participants in the pneumatic survey were asked to rank how important each of the 2021 Capability Improvements would be in increasing the use of pneumatics in each Customer Strategy. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		CAPABILITY IMPROVEMENTS						
CUSTOMER STRATEGIES	N	Improving pneumatic control systems	Improving ability to monitor, gather, and use data generated from pneumatic products and/or systems	Improving the reliability and/or durability of pneumatic products and/or systems	Increasing the energy efficiency of pneumatic products and/or systems	Increasing the power density of pneumatic products and/or systems	Reducing the environmental impact of pneumatic products and/or systems	Reducing the lead time for pneumatic products and their control elements
Autonomy	9	3.556	3.778	3.667	2.889	3.111	2.778	3.667
Compactness	9	3.444	3.444	3.667	3.222	3.222	2.778	3.333
Connectivity	8	4.000	4.375	3.750	3.250	3.125	2.750	3.750
Electrification	8	3.625	3.250	2.875	3.125	3.250	2.750	3.375
Energy Efficiency	8	3.500	3.125	3.375	4.000	3.000	3.250	3.750
Maintenance	8	3.500	4.125	4.250	3.125	2.500	2.875	3.500
Materials	8	2.500	2.500	3.125	2.500	2.625	3.375	2.750
Noise	8	3.500	2.625	3.500	2.875	2.500	2.625	3.125
All Responses	66	3.455	3.409	3.530	3.121	2.924	2.894	3.409

5.000 - 4.500
4.499 - 4.000
3.999 - 3.500
3.499 - 3.000
2.999 - 2.500
2.499 - 2.000

Generally speaking, the importance of these Capability Improvements was ranked lower for pneumatics than it was for hydraulics. These results show the three Capability Improvements with the greatest potential impact on the use of pneumatics are improving reliability/durability, improving control systems, and improving use of data.

Suggestions for New Capability Improvements

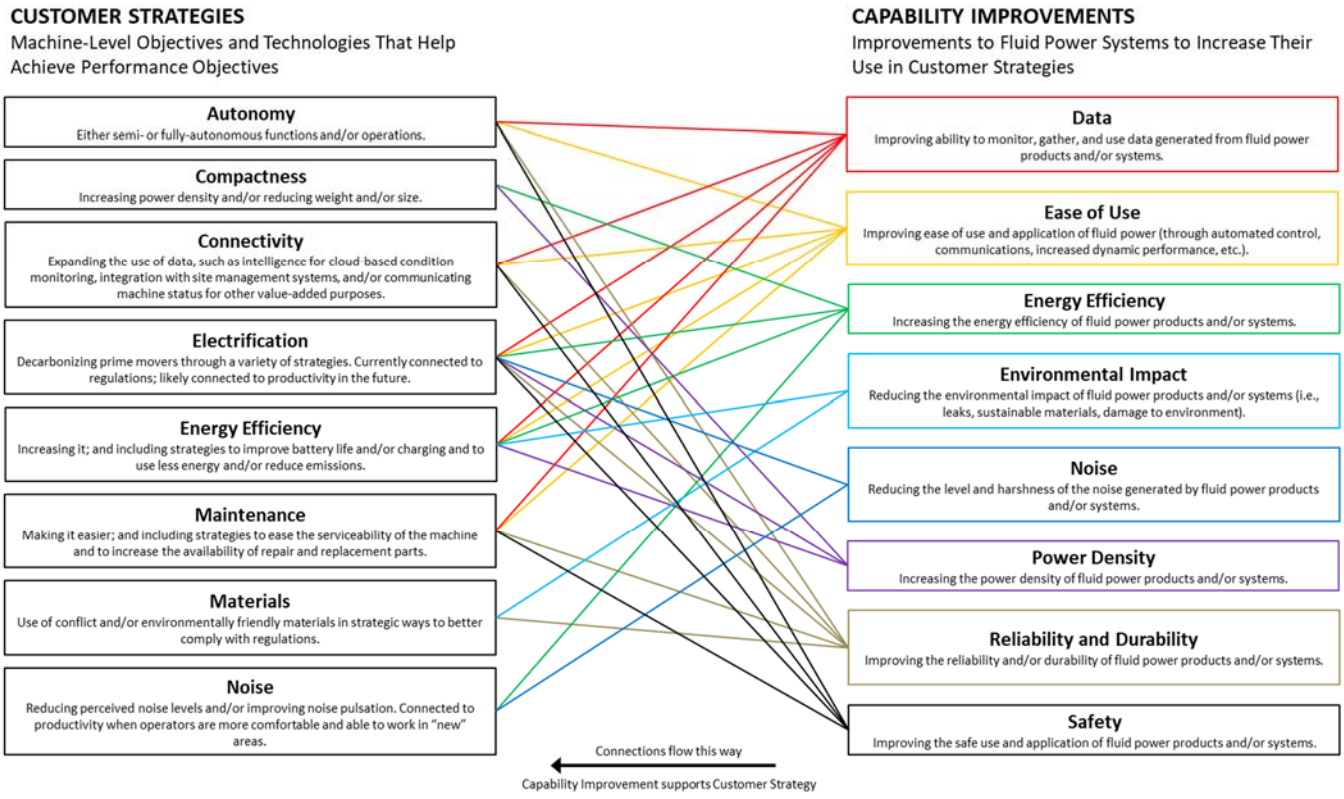
Survey responders also provided suggestions for new Capability Improvements that had emerged since the time of the 2021 NFPA Technology Roadmap. The majority of these suggestions were collected from the hydraulic survey, and included:

- Ease of use and ease of application of technology (putting systems together)
- Improving communication protocols and data management strategies
- Increasing safety
- Reduced noise (level and quality)
- Training (more knowledge of fluid power benefits, workforce development)

Identification of Capability Improvements for the 2023 NFPA Roadmap

The survey data on existing Capability Improvements and the suggestions for new Capability Improvements were reviewed by the NFPA Roadmap Committee at its March 2, 2023 meeting. In discussing which Capability Improvements to prioritize for the 2023 Roadmap, the Committee

discussed each of these items in turn, and determined which items would be positioned as 2023 Capability Improvements, and how each would be connected to the Customer Strategies. The outcome of that discussion is shown below.



DEFINITION OF PRE-COMPETITIVE RESEARCH

Pre-competitive research is performed at the time in the technology development cycle when interested, but potentially competitive parties agree that there is value to be gained from a collaborative rather than a competitive approach.

It generally resides in the middle ground between fundamental basic research conducted mainly in universities and proprietary research performed or directed mainly by companies. It can be performed to develop new technologies or to determine the market readiness of new technologies.

For the purposes of developing the Research Areas and Targets included in this report, Roadmap Committee members focused on pre-competitive activities and recommendations.

RESEARCH AREAS

Research Areas are the broad areas of pre-competitive investigation that could assist in bringing about the Capability Improvements.

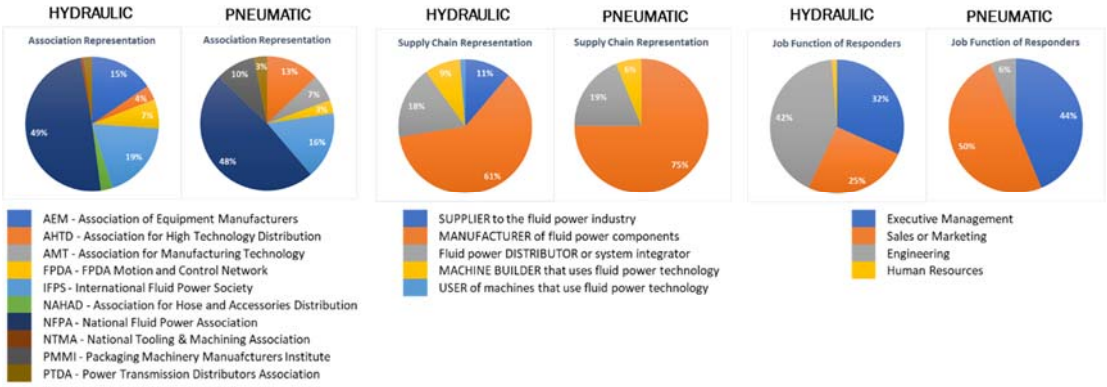
In the 2021 NFPA Technology Roadmap, the following nine Research Areas were identified as those most likely to bring about the improvements defined by the Capability Improvements.

- Improve the controllability of fluid power systems
- Advance sensor technologies used in fluid power systems
- Explore novel fluid power system architectures
- Develop new fluid power components
- Improve use of data analytics in fluid power systems
- Develop/apply new materials in fluid power components and systems
- Optimize the use of fluids and lubrication in fluid power systems
- Optimize the use of seal technologies in fluid power systems
- Develop/apply new manufacturing technologies for fluid power components and systems

Following the identification of the final Capability Improvements for the 2023 NFPA Technology Roadmap, the NFPA Roadmap Committee established eight Working Groups, one for each Capability Improvement, and tasked each with identifying a prioritized list of pre-competitive Research Areas and Targets that could best assist in bringing about its Capability Improvement.

<u>Survey on Fluid Power Research Areas</u>

To assist the Working Groups with this task, NFPA conducted two surveys in April 2023 to assess the usefulness of these Research Areas in bringing about the improvements described by the 2023 Capability Improvements, and to determine if any new Research Areas had emerged since the time of the 2021 NFPA Technology Roadmap. One survey asked about hydraulic Research Areas; the other about pneumatic Research Areas. Together, the surveys received responses from 96 individuals across the fluid power supply chain, including a large percentage from the NFPA Roadmap Committee.



Importance of Existing Research Areas

Participants in the hydraulic survey were asked to rank how important each of the 2021 Research Areas would be in making a significant impact on each 2023 hydraulic Capability Improvement. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		RESEARCH AREAS								
CAPABILITY IMPROVEMENTS	N	Improve the controllability of hydraulic systems	Advance sensor technologies used in hydraulic systems	Explore novel hydraulic system architectures	Develop new hydraulic components	Improve use of data analytics in hydraulic systems	Develop/apply new materials in hydraulic components and systems	Optimize the use of fluids and lubrication in hydraulic systems	Optimize the use of seal technologies in hydraulic systems	Develop/apply new manufacturing technologies for hydraulic components and systems
Data	67	3.940	4.045	3.448	3.866	4.060	3.328	3.045	2.940	3.463
Ease of Use	63	4.206	4.190	3.540	3.635	3.937	3.190	2.873	2.921	3.063
Energy Efficiency	57	4.000	4.228	4.000	3.947	4.158	3.456	3.684	3.333	3.281
Environmental Impact	55	3.327	3.618	3.418	3.545	3.509	3.982	4.036	3.909	3.636
Noise	54	3.611	3.556	3.778	4.019	3.426	3.593	3.315	2.870	3.111
Power Density	54	3.370	3.463	3.889	4.333	3.278	4.056	3.407	3.222	3.444
Reliability and Durability	55	3.400	3.782	3.509	3.764	3.855	4.145	3.800	3.927	3.527
Safety	53	4.132	4.189	3.396	3.453	3.642	3.189	2.962	3.321	2.943
All Responses	458	3.762	3.895	3.618	3.819	3.749	3.603	3.376	3.290	3.310

5.000 - 4.500
4.499 - 4.000
3.999 - 3.500
3.499 - 3.000
2.999 - 2.500
2.499 - 2.000

These results show significant variation in which Research Areas would have the greatest impact on which Capability Improvements. Two Research Areas failed to score above an average of 4.000 for any of the hydraulic Capability Improvements: Optimizing seal technologies and developing new manufacturing technologies.

Participants in the pneumatic survey were asked to rank how important each of the 2021 Research Areas would be in making a significant impact on each 2023 pneumatic Capability Improvement. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		RESEARCH AREAS								
CAPABILITY IMPROVEMENTS	N	Improve the controllability of pneumatic systems	Advance sensor technologies used in pneumatic systems	Explore novel pneumatic system architectures	Develop new pneumatic components	Improve use of data analytics in pneumatic systems	Develop/apply new materials in pneumatic components and systems	Optimize the use of fluids and lubrication in pneumatic systems	Optimize the use of seal technologies in pneumatic systems	Develop/apply new manufacturing technologies for pneumatic components and systems
Data	16	3.938	4.000	3.375	3.750	4.063	3.375	3.063	3.063	3.500
Ease of Use	14	4.143	3.857	3.429	3.714	3.786	3.286	3.071	3.357	3.571
Energy Efficiency	13	4.000	3.692	3.615	4.000	3.615	3.538	3.000	3.154	3.769
Environmental Impact	12	3.333	3.500	3.167	3.917	3.250	3.667	3.583	3.917	3.417
Noise	12	4.167	3.500	3.417	3.833	3.083	3.750	3.500	3.333	3.500
Power Density	12	3.667	3.667	3.750	3.917	3.667	3.833	2.583	3.083	3.750
Reliability and Durability	12	3.667	3.333	3.250	4.000	3.500	4.083	3.500	4.083	3.583
Safety	12	3.917	3.750	3.500	3.750	3.500	3.417	2.667	2.917	3.083
All Responses	103	3.864	3.680	3.437	3.854	3.583	3.602	3.117	3.350	3.524

5.000 - 4.500
4.499 - 4.000
3.999 - 3.500
3.499 - 3.000
2.999 - 2.500
2.499 - 2.000

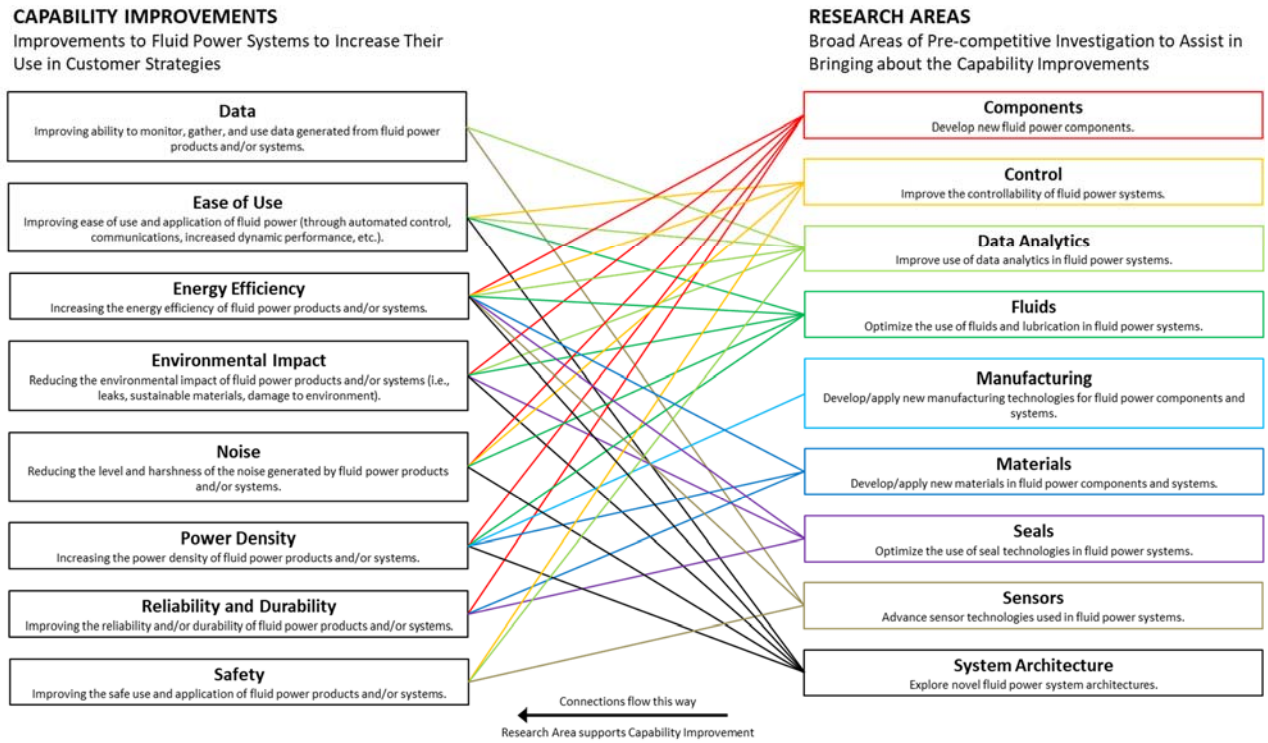
These results also show significant variation in which Research Areas would have the greatest impact on which Capability Improvements. Three Research Areas failed to score above an average of 4.000 for any of the pneumatic Capability Improvements: Exploring novel system architectures, optimizing use of fluids and lubrication, and developing new manufacturing technologies.

Suggestions for New Research Areas

In addition to ranking the importance of the existing Research Areas, participants were also asked to suggest any additional Research Areas that they would suggest to make a significant impact on each Capability Improvement. In reviewing these suggestions, the NFPA Roadmap Committee determined that many of the suggestions would require market-based rather than technology-based improvements in order to be effective, and therefore would not be appropriate for incorporation into a technology development roadmap.

Identification of Research Areas for the 2023 NFPA Roadmap

The survey data on existing Research Areas and the suggestions for new Research Areas were reviewed by each of the Capability Improvement Working Groups at their meetings held in April or May 2023. In discussing which Research Areas to prioritize for their Capability Improvement, the Working Groups discussed each item in turn, determined which items would be positioned as 2023 Research Areas, and how each would be connected to the Capability Improvements. The outcomes of those discussions are shown below.



RESEARCH TARGETS FOR EACH CAPABILITY IMPROVEMENT

Research Targets are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

Following the identification of the final Capability Improvements for the 2023 NFPA Technology Roadmap, the NFPA Roadmap Committee established eight Working Groups, one for each Capability Improvement, and tasked each with identifying a prioritized list of pre-competitive Research Areas and Targets that could best assist in bringing about its Capability Improvement.

These Working Groups met in April or May 2023. In addition to selecting the Research Areas prioritized for their Capability Improvement, each Group developed a list of Research Targets, designed to provide additional guidance for organizations that wish to pursue research projects of importance to the fluid power industry. Specifically, initiatives that are designed to bring about each of the following Capability Improvements may wish to focus on the nested Research Areas and Targets described.

I. DATA: Improving ability to monitor, gather, and use data generated from fluid power products and/or systems.

- **A. Data Analytics:** Improve use of data analytics in fluid power systems.
  1. **Data Processing:** Improve data processing capabilities through the use of edge computing (on-board sensing and processing) and/or through the use of cloud computing.
  2. **Data Analysis:** Improve data analysis capabilities through the use of artificial intelligence and/or machine learning.
  3. **Data Utilization:** Apply improved data gathering, processing, and analysis capabilities to specific machine or system outcomes, including increased efficiency, automated functions and/or operation, and end-of-life prognostics and preventative maintenance.

- **B. Sensors:** Advance sensor technologies used in fluid power systems.
  1. **Wireless Sensors:** Improve the capabilities, reliability, and availability of wireless sensors for use in fluid power systems. Pursue strategies to improve their connectivity to data-generating devices, to embed them in components and systems and lowering their maintenance requirements (no need to replace batteries or recalibrate, self-diagnosing, failure-proof), and to lower their cost without reducing their effectiveness.
  2. **Sensor Materials:** Develop and apply sensor materials that are non-aluminum and non-sparking.

II. EASE OF USE: Improving ease of use and application of fluid power (through automated control, communications, increased dynamic performance, etc.).

A. **Control:** Improve the controllability of fluid power systems.
   1. **Standardize:** Develop and apply standard electronic control schemes.
   2. **Wireless Control:** Increase and improve options for wireless control.
   3. **Autonomous Function:** Improve capabilities for autonomous function of fluid power systems.
   4. **Programming:** Reduce the amount of code needed for effective control (e.g., through transition to voice-activated or other "simplified interface" control systems).

B. **Data Analytics:** Improve use of data analytics in fluid power systems.
   1. **Data Processing:** Improve data processing capabilities through the use of edge computing (on-board sensing and processing) and/or through the use of cloud computing.
   2. **Data Analysis:** Improve data analysis capabilities through the use of artificial intelligence and/or machine learning.
   3. **Data Utilization:** Apply improved data gathering, processing, and analysis capabilities to specific machine or system outcomes, including automated functions and/or operation, and end-of-life prognostics and preventative maintenance.

C. **Fluids:** Optimize the use of fluids and lubrication in fluid power systems.
   1. **Environmentally-Friendly:** Develop longer-lasting, environmentally-friendly fluids (so that they can be replaced less often and generate less concern over spills).

D. **System Architecture:** Explore novel fluid power system architectures.
   1. **Simulation Tools:** Develop and standardize digital modeling and simulation methods for fluid power components and systems, especially those that allow for analysis of fluid dynamics and efficiency maps.
   2. **Plug and Play:** Enable "plug and play" connectivity for fluid power components and their interface with electronic controls.
   3. **Maintenance:** Develop new diagnostic tools to find faults and more quickly correct them.

III. ENERGY EFFICIENCY: Increasing the energy efficiency of fluid power products and/or systems.

A. **Components:** Develop new fluid power components.
   1. **Cartridge Valves:** Improve ability of cartridge valves to function in high pressure applications; and to act as independent metering valves.

B. **Control:** Improve the controllability of fluid power systems.
   1. **On-Demand Power:** Improve and develop on-demand power capabilities (running power units only when needed).

C. **Data Analytics:** Improve use of data analytics in fluid power systems.

1. **Standardization:** Standardize data gathering and analysis processes so improvements can be shared across platforms and applications.

D. Fluids: Optimize the use of fluids and lubrication in fluid power systems.
1. **Pressure Drop:** Develop fluids which will reduce pressure drop and/or reduce number of components.

E. Materials: Develop/apply new materials in fluid power components and systems.
1. **PFAS:** Develop new materials that are PFAS-compliant for fluid power components.
2. **Coatings:** Develop coatings that reduce friction and heat (e.g., chrome replacements on the horizon).

F. Seals: Optimize the use of seal technologies in fluid power systems.
1. **Friction:** Optimize seal geometry and materials while maintaining fluid film thickness resulting in a reduction of friction.

G. Sensors: Advance sensor technologies used in fluid power systems.
1. **Position Detection:** Improve position detection methods, especially in ways that reduce the amount of space needed for this function.
2. **Availability:** Increase the availability and affordability of sensors (e.g., pressure/linear transducers) so they can be more widely used across the system ("borrow" strategies from other industries (automotive, cell phones (MEMS))).

H. System Architecture: Explore novel fluid power system architectures.
1. **Distributed Systems:** Develop more efficient, distributed system architectures (multiple power sources with synchronized control of both motors and pumps).
2. **Flow and Pressure:** Develop methods to control both flow and pressure, utilizing each as needed for optimized energy recovery and efficiency.

IV. ENVIRONMENTAL IMPACT: Reducing the environmental impact of fluid power products and/or systems (i.e., leaks, sustainable materials, damage to environment).

A. Components: Develop new fluid power components.
1. **Filter Media:** Explore new filter media that are compatible with environmentally-friendly fluids.
2. **Circular Economy:** Increase participation in the "circular economy" (i.e., make components of biodegradable or other sustainable materials, increasing the ease of reutilization and disposal of materials at end-of-life).
3. **Refurbishment:** Extend the serviceability, re-manufacturing, and refurbishment of fluid power components.
4. **Lifecycle Determination:** Standardize and apply lifecycle determination and replacement procedures for fluid power components (eliminate run-to-failure model).

B. Data Analytics: Improve use of data analytics in fluid power systems.
1. **Data Utilization:** Apply improved data gathering, processing, and analysis capabilities to specific machine or system outcomes, including end-of-life prognostics and preventative maintenance.

C. Fluids: Optimize the use of fluids and lubrication in fluid power systems.
1. **Oil Volume:** Reduce the volume of oil needed in machines.
2. **Extend Life:** Extend the life of existing fluids (e.g., reducing the heat generated in the system, limiting water ingression).
3. **Environmentally-Friendly:** Develop biodegradable fluids that reduce leakage and improve efficiency.

D. Seals: Optimize the use of seal technologies in fluid power systems.
1. **Surface Finish:** Optimize surface finishes (e.g., through the use of coatings) for better compatibility with seals and to reduce external leakage.
2. **Seal Materials:** Optimize use of materials and geometries to eliminate external leakage and reduce NVH.

E. System Architecture: Explore novel fluid power system architectures.
1. **Containment:** Develop ways to contain and capture leaked fluid from entering the environment.
2. **Less Cooling:** Develop system architectures that require less cooling.

V. NOISE: Reducing the level and harshness of the noise generated by fluid power products and/or systems.

A. Components: Develop new fluid power components.
1. **Design Tools:** Develop new design analysis tools for hydraulic component and system noise attenuation that better recognize the noise effects of high-pressure operation.
2. **Materials:** Explore the use of composites or other “noise-dampening” materials in the construction of fluid power components.
3. **Component Design:** Explore and develop new reservoir and filter designs (e.g., centrifugal) to more effectively remove entrained air.
4. **Optimize Pumps:** Optimize pump designs, including inherently quiet vane or internal crescent pumps, for tight integration with variable-speed electric motors.

B. Control: Improve the controllability of fluid power systems.
1. **Entrained Air:** Develop methods to remove entrained air from hydraulic fluid.
2. **Required Flow:** Improve methods for providing only the flow needed for actual work.

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

1. **Air Release:** Analyze and optimize the air-release properties of hydraulic oils for reducing cavitation and thereby noise.

D. System Architecture: Explore novel fluid power system architectures.

1. **Operating Range:** Narrow the operating range, particularly the speed, of the system (mostly the pump), and then optimize the valving and size the attenuators for lower noise levels ("borrow" strategies from the industrial world).
2. **Installation:** Develop and adopt better practices for hydraulic system installation (e.g., hose routings, isolation mounts, bracket stiffness).
3. **Encasement:** Experiment with methods to encase systems or system components in sound-proof chambers or strategies (e.g., submerge e-pump in reservoir).
4. **Energy Efficiency:** Increase energy efficiency of systems (as a way of reducing noise).

VI. POWER DENSITY: Increasing the power density of fluid power products and/or systems.

A. Components: Develop new fluid power components.

1. **Power Density:** Develop more power dense components; ensure their safe use and application.

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

1. **Power Density:** Optimize the use of fluids for power dense operation.

C. Manufacturing: Develop/apply new manufacturing technologies for fluid power components and systems.

1. **Additive:** Apply additive manufacturing (for example, produce high pressure capable components and develop improved design tools for the additive manufacturing of fluid power components).

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

1. **Higher Pressure:** Test and record the maximum pressure ratings for different materials used in fluid power components; Improve ability of fluid power components (e.g., manifolds, hoses, fittings) to handle higher pressures.
2. **Additive:** Develop/optimize materials used for additive manufacturing for increased power density.

E. System Architecture: Explore novel fluid power system architectures.

1. **Power Density:** Explore new system architectures that are more compact/power dense (e.g., distributed hydraulics).
2. **Simulation Tools:** Standardize and deepen the parameterization of digital modeling/simulation methods in hydraulic components (motors, pumps, accumulators, filters); Use resulting models to drive towards smaller, safer components.

VII. RELIABILITY AND DURABILITY: Improving the reliability and/or durability of fluid power products and/or systems.

A. Components: Develop new fluid power components.
1. **Prediction Tools:** Analyze impact of pressure, temperature, and other operational realties on components and develop modeling and prediction tools for their lifecycle and potential failure.
2. **Surface Finish:** Review, test and determine surface finish requirements for reliable and durable operation of fluid power components.
3. **Test Protocols:** Develop standardized test protocols for the reliability of key fluid power components.
4. **Refurbishment:** Develop and adopt component designs that allow for easier rebuilding or refurbishment where most needed.

B. Materials: Develop/apply new materials in fluid power components and systems.
1. **Surface Finish:** Improve surface finish and substrate properties (through use of coatings, nanotechnologies, or otherwise) (e.g., strength, hardness, anti-friction, anti-wear and corrosion-resistant properties).
2. **Coatings:** Develop and more widely apply coatings not dependent on hexavalent chrome.

C. Seals: Optimize the use of seal technologies in fluid power systems.
1. **Seal Materials:** Develop new and sustainable seal and wear-ring technologies (materials, profiles, designs) that can resist wear (e.g., more compatible with anti-wear and other additives in common fluids).
2. **Prediction Tools:** Improve ability to measure and predict seal wear and life (e.g., through use of RFIDs or other monitoring devices).

VIII. SAFETY: Improving the safe use and application of fluid power products and/or systems.

A. Control: Improve the controllability of fluid power systems.
1. **Failure Mode:** Improve ability to bring about safe states after unexpected failure.
2. **Range Limits:** Improve ability to keep system from functioning in unsafe spaces (e-fencing, virtual floors, etc.).
3. **Electronic Components:** Increase the safe integration of electronic components with fluid power systems.

B. Data Analytics: Improve use of data analytics in fluid power systems.
1. **Artificial Intelligence:** Apply artificial intelligence/machine learning to the safe control and function of fluid power systems (e.g., preventative maintenance, move to safe-mode, perform repetitive tasks).
2. **Edge Computing:** Leverage edge computing to increase safe use of fluid power.

3. **Interfaces:** Improve human/machine interfaces and other data displays to increase safe use and operation.

C. **Sensors:** Advance sensor technologies used in fluid power systems.
   1. **Visual Sensors:** Reduce reliability on visual sensors, especially on worksites with visual occlusions.
   2. **Real-Time Info:** Gather and increase use of real-time job site information in machine and system operation (known and discovered barriers in environment to avoid).
   3. **Availability:** Increase availability, affordability, and safety documentation of sensors.

PRIORITZED RESEARCH TARGETS FOR EACH RESEARCH AREA

Research Targets are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

Following the Working Group meetings in April and May 2023, the NFPA Roadmap Committee met on June 1, 2023 to review the Research Targets that had been recommended by the each of the eight Working Groups and select those most likely to have the greatest impact on advancing each Research Area and, by extension, improving fluid power's capabilities and ability to address the needs described by the Customer Strategies.

In making these determinations, the commonality of some Research Targets were observed, and edits were often made to capture similar ideas into single statements.

COMPONENTS: Develop new fluid power components.

- **Prediction Tools:** Analyze impact of pressure, temperature, and other operational realties on components and develop modeling and prediction tools for their lifecycle and potential failure.
- **Power Density:** Develop more power dense components; ensure their safe use and application.

CONTROL: Improve the controllability of fluid power systems.

- **On-Demand Power:** Improve and develop on-demand power capabilities (running power units only when needed).

DATA ANALYTICS: Improve use of data analytics in fluid power systems.

- **Data Utilization:** Apply improved data gathering, processing, and analysis capabilities to specific machine or system outcomes, including increased efficiency, automated functions and/or operation, and end-of-life prognostics and preventative maintenance.

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

- **Environmentally-Friendly:** Develop longer-lasting, biodegradable, environmentally-friendly fluids that reduce leakage and improve efficiency.

MANUFACTURING: Develop/apply new manufacturing technologies for fluid power components and systems.

- **Additive:** Develop cost-competitive additive materials, develop improved design tools for, and apply additive manufacturing to produce high pressure capable components.

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

- **Coatings:** Develop coatings that reduce friction and heat (e.g., replacement for hexavalent chrome and PFAS compliant).

- **Higher Pressure:** Test and record the maximum pressure ratings for different materials used in fluid power components; Improve ability of fluid power components (e.g., manifolds, hoses, fittings) to handle higher pressures.

SEALS: Optimize the use of seal technologies in fluid power systems.

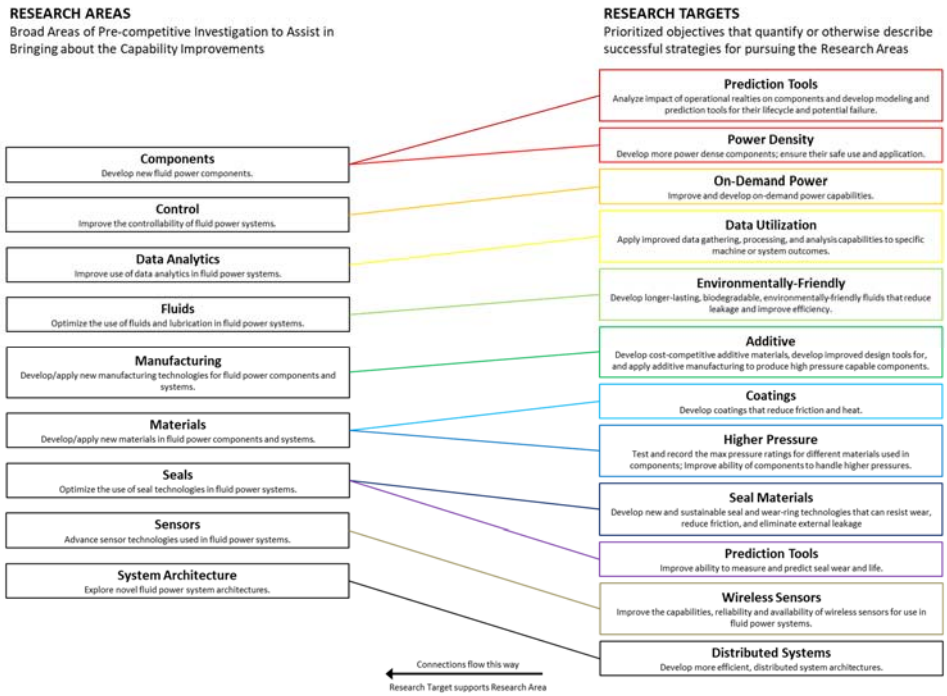
- **Seal Materials:** Develop new and sustainable seal and wear-ring technologies (materials, geometries, profiles, designs) that can resist wear (e.g., more compatible with anti-wear and other additives in common fluids), reduce friction, and eliminate external leakage.
- **Prediction Tools:** Improve ability to measure and predict seal wear and life (e.g., through use of RFIDs or other monitoring devices).

SENSORS: Advance sensor technologies used in fluid power systems.

- **Wireless Sensors:** Improve the capabilities, reliability and availability of wireless sensors for use in fluid power systems. Pursue strategies to improve their position detection methods, to improve their connectivity to data-generating devices, to embed them in components and systems and lowering their maintenance requirements (no need to replace batteries or recalibrate, self-diagnosing, failure-proof), and to lower their cost without reducing their effectiveness. Explore the application of successful strategies in other industries (automotive, cell phones, etc.).

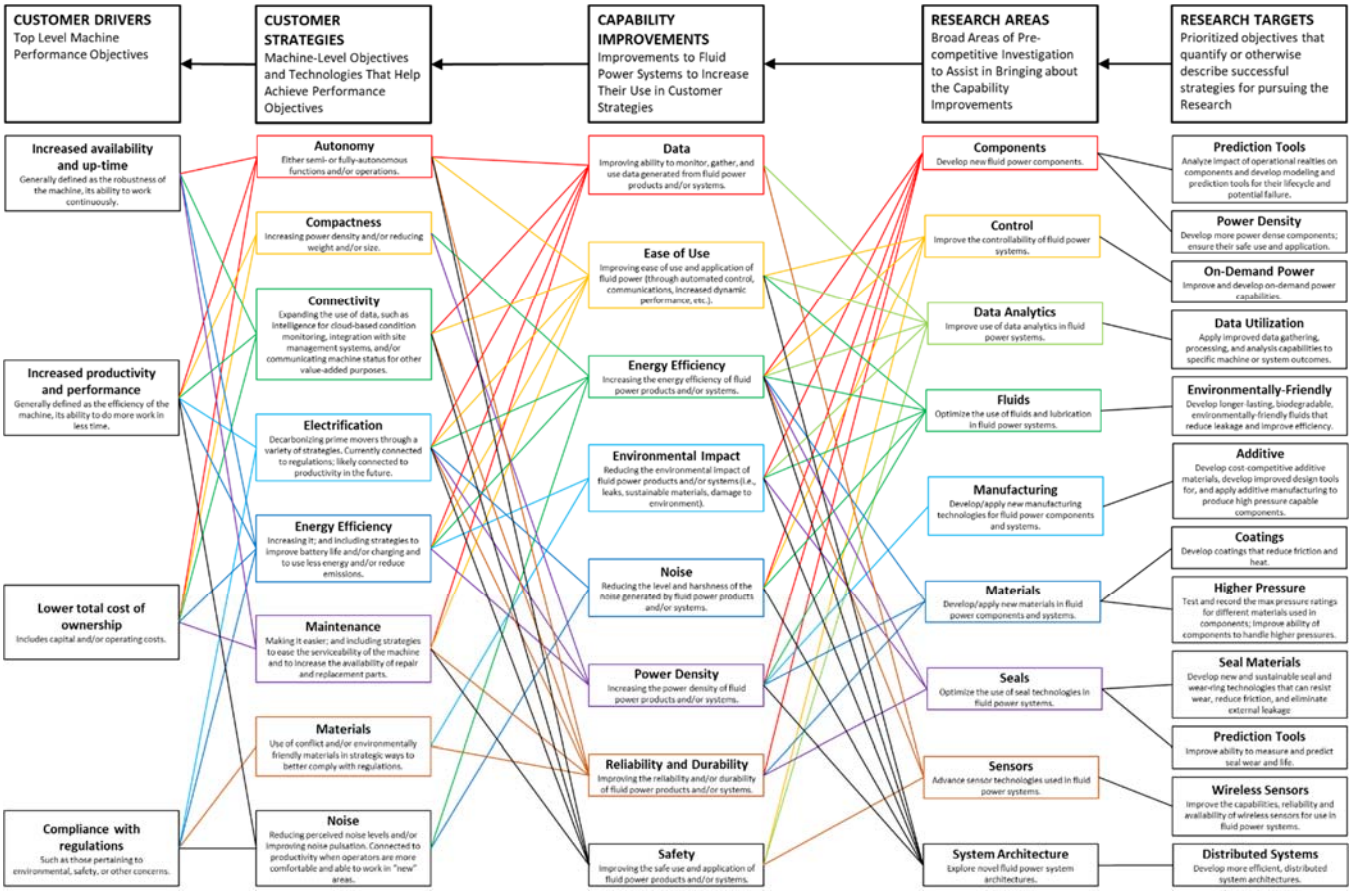
SYSTEM ARCHITECTURE: Explore novel fluid power system architectures.

- **Distributed Systems:** Develop more efficient, distributed system architectures (multiple power sources with synchronized control of both motors and pumps).



FULL TECHNOLOGY ROADMAP SCHEMATIC

A schematic of the full 2023 NFPA Technology Roadmap, showing all the connections between the Customer Drivers, Customer Strategies, Capability Improvements, Research Areas, and Prioritized Research Targets is shown below. A hi-res version of this schematic is available upon request from the NFPA office.



RELATED PROJECTS AND ACTIVITIES

In the course of developing the 2023 NFPA Technology Roadmap, the NFPA Roadmap Committee explored and discussed a wide variety of issues of importance to the fluid power industry. Several were not included in the 2023 NFPA Technology Roadmap because, although important, they do not represent or otherwise relate to the research and development of fluid power technologies. A list of these related projects and activities is included below. Future Roadmap Committees should consider these issues in the development of future Technology Roadmaps.

Standardization

Several initiatives to standardize practices or technologies of importance to the fluid power industry were discussed. These initiatives included:

- **Data Gathering and Analysis:** Standardize data gathering and analysis processes so improvements can be shared across platforms and applications.
- **Electronic Control:** Develop and apply standard electronic control schemes.
- **Installation:** Develop and adopt better practices for hydraulic system installation (e.g., hose routings, isolation mounts, bracket stiffness).
- **Lifecycle Determination:** Standardize and apply lifecycle determination and replacement procedures for fluid power components (eliminate run-to-failure model).
- **Material Strength:** Consider the creation of material strength standards for additive projects.
- **Reliability Test Protocols:** Develop standardized test protocols for the reliability of key fluid power components.
- **Simulation Tools:** Standardize and deepen the parameterization of digital modeling/simulation methods in hydraulic components (motors, pumps, accumulators, filters); Use resulting models to drive towards smaller, safer components.

It was agreed that these ideas should be shared with the ISO committee responsible for fluid power standards for possible implementation.

Prediction/Design Tools

It was also noted that Prediction/Design Tools was a topic that crossed many areas. Committee members agreed that predictive tools that help gather real data would help frame and execute on actual R&D projects.

COMMITTEE AND WORKING GROUPS

The following individuals served on the NFPA Roadmap Committee and participated in the various meetings and Working Groups it convened to help complete this report.

Chair

- Bradlee Dittmer, NORGREN

Vice Chair

- Steve Meislahn, Sun Hydraulics

Participants at Roadmap Committee Meetings

Representative	Organization	1/12/2023	3/2/2023	6/1/2023
Ed Danzer	6K Products		X	X
Brian Rhode	Afton Chemical Corporation	X		
Blake Cawley	AMETEK APT	X		X
Benjamin Moses	Association for Manufacturing Technology	X	X	X
Bill Shepard	BDI		X	
Cory Geers	BDI	X	X	
Jon Frey	Bosch Rexroth Corporation	X	X	X
Christian Eitel	Bucher Hydraulics	X	X	
Todd Harmon	Canfield Industries		X	X
Mike Gust	CCEFP	X		X
Dominic Catanzarite	Daman Products	X	X	X
Matthew Giloth	Daman Products		X	X
Jamie LeClair	Danfoss			X
Kevin Lingenfelter	Danfoss			X
Mike Betz	Danfoss	X	X	X
Timothy Meehan	Danfoss			X
Paul Gilbert	Danfoss Power Solutions			X
Jason Palmer	Delta Computer Systems		X	X
David Yale	Delta Power Company		X	
Ivan Sheffield	Des-Case		X	X
Adam Livesay	Elevat	X	X	X
Jonathan Gamble	Enfield Technologies	X	X	X
Mitchell Wiese	Faster Couplings	X		
John Holmes	Festo			X
Brent Rogers	Festo Corporation	X		
Matt Loeffler	FORCE America	X	X	X

Representative	Organization	1/12/2023	3/2/2023	6/1/2023
Sudarshan Sharma	Galland Henning Nopak			X
Tom Miklos	Galland Henning Nopak		X	X
Todd Pinkelman	Gates	X		
Ron Akers	Gefran			X
Chuck White	Hallite Seals			X
Tim Erickson	HED			X
Ben Holter	Husco			X
Chris Kolbe	HYDAC			X
Russell Evans	HYDAC		X	
Russ Schneidewind	Hydraforce	X		X
Scott Nagro	Hydraforce	X		
Mark Bokorney	Hydra-Power Systems	X	X	X
David Shier	Hydro-Gear			X
Narendra Gupta	Hyster-Yale Group	X	X	X
David Tetzlaff	Innovative Hydraulics			X
Brian Steward	Iowa State University			X
Joe Jackan	JARP Industries	X	X	X
Jeff Bauer	John Deere		X	X
Paul Marvin	John Deere		X	X
Tom Vander Meulen	Kawasaki Precision Machinery	X	X	
Michael Miles	KersTech, Inc.		X	X
Douglas Seeger	Komatsu			X
Roy Schmoutz	Komatsu		X	
Patrick Green	Kraft Fluid Systems Inc.			X
Donald St. Clair	Master Pneumatic-Detroit, Inc.	X		
Douglas Lacina	Milwaukee Cylinder	X		
Paul Michael	Milwaukee School of Engineering	X		X
Dave Geiger	Moog	X	X	X
Jason Gilham	Moog			X
Thomas Ehmann	Moog			X
Tim Kolankowski	Moog			X
Bob Mosey	Mosey's Production Machinists, Inc.		X	
Larry Wesley	Muncie Power Products, Inc.		X	
Andy Nackovic	National Tube Supply	X		
Jessica Young	National Tube Supply			X
Brad Dittmer	NORGREN	X		X
Howard Zhang	Parker Hannifin	X		X
Ron Hibbler	Proportion-Air	X	X	X
Kevin Brown	QP Hydraulics	X		

Representative	Organization	1/12/2023	3/2/2023	6/1/2023
Jay Dalal	ROSS Controls	X	X	X
Allan Scales	RSA, Inc.	X		
Scott McCambridge	SMC Corporation of America		X	
Jeff Andrasik	Smithers		X	X
Steven Meislahn	Sun Hydraulics	X	X	
Zeke Metzler	Texcel	X	X	X
Joey Kadziolka	Tigercat			X
Furat Al-Saleem	Trelleborg Sealing Solutions	X	X	X
John McLaughlin	Trelleborg Sealing Solutions	X	X	
Michael Cook	Trelleborg Sealing Solutions	X	X	X
Nancy Getz	Trelleborg Sealing Solutions	X		
Trevor Combs	Trelleborg Sealing Solutions		X	X
Rick Guidish	VIS Hydraulics			X
Enrico Baiocchi	Walvoil Fluid Power			X

Working Group #1: Data

- Blake Cawley, AMETEK APT
- Benjamin Moses, Association for Manufacturing Technology
- Jason Palmer, Delta Computer Systems
- Adam Livesay, Elevat
- Jonathan Gamble, Enfield Technologies
- Tim Erickson, HED
- Brian Steward, Iowa State University
- Brad Dittmer, NORGREN
- Kent Sowatzke, NORGREN
- Jose Garcia Bravo, Purdue University
- Allan Scales, RSA, Inc.
- Michael Cook, Trelleborg Sealing Solutions

Working Group #2: Ease of Use

- David Yale, Delta Power Company
- Mitchell Wiese, Faster Couplings
- Tom Miklos, Galland Henning Nopak
- David Shier, Hydro-Gear
- Roy Schmoutz, Komatsu
- Patrick Green, Kraft Fluid Systems Inc.
- Douglas Lacina, Milwaukee Cylinder
- Bob Mosey, Mosey's Production Machinists, Inc.
- Jessica Young, National Tube Supply

- Brad Dittmer, NORGREN
- Ron Hibbler, Proportion-Air

Working Group #3: Energy Efficiency

- Ed Danzer, 6K Products
- Jeff Zimmerer, Automated Hydraulics
- Matthew Giloth, Daman Products
- Chuck White, Hallite Seals
- David Shier, Hydro-Gear
- Chuck Schreiner, Hydrotech
- Joe Jackan, JARP Industries
- Douglas Seeger, Komatsu
- Dave Geiger, Moog
- Howard Zhang, Parker Hannifin
- John McLaughlin, Trelleborg Sealing Solutions

Working Group #4: Environmental Impact

- Bill Shepard, BDI
- Cory Geers, BDI
- Jon Frey, Bosch Rexroth Corporation
- Chuck White, Hallite Seals
- Mark Paxton, HANSA-FLEX USE
- Larry Gerken, Hy-Pro Filtration
- Jeff Andrasik, Smithers
- Furat Al-Saleem, Trelleborg Sealing Solutions

Working Group #5: Noise

- Christian Eitel, Bucher Hydraulics
- Mike Gust, CCEFP
- Paul Michael, Milwaukee School of Engineering
- Nancy Getz, Trelleborg Sealing Solutions

Working Group #6: Power Density

- Paul Byrne, Burnside America
- Dominic Catanzarite, Daman Products
- Mike Betz, Danfoss
- Paul Gilbert, Danfoss Power Solutions
- Matt Loeffler, FORCE America
- Russ Schneidewind, Hydraforce
- Scott Nagro, Hydraforce

- Mark Bokorney, Hydra-Power Systems
- Michael Miles, KersTech, Inc.
- Steven Meislahn, Sun Hydraulics

Working Group #7: Reliability and Durability

- Mike Betz, Danfoss
- Sudarshan Sharma, Galland Henning Nopak
- Chuck White, Hallite Seals
- Jeff Bauer, John Deere
- Larry Wesley, Muncie Power Products, Inc.
- Zeke Metzler, Texcel
- Trevor Combs, Trelleborg Sealing Solutions

Working Group #8: Safety

- Sharvari Jayant Divey-Teall, Crown Equipment Corporation
- Tim Erickson, HED
- Ben Holter, Husco
- Paul Marvin, John Deere
- Jay Dalal, ROSS Controls
- Chris Vandermeer, Scanreco

Staff Organization, Facilitation and Writing

- Eric Lanke, NFPA