Summary of Prepared Statement by Dr. Klaus Brun **August 17, 2018**
Machinery Program Director, **Southwest Research Institute**
For the House Science, Space & Technology Committee
Subcommittee on Energy and Environment

Cheap and reliable energy is one of the critical drivers of our economy. The sCO_2 power cycle development has been a major collaborative effort between industry, government, and research institutes to make electricity cheaper, more reliable, and also cleaner. For the last 250 years the majority of fossil-fueled power plants have been using steam and air. But technology development never stands still and we must pursue the next generation of better power plants. The sCO_2 power cycle is not a new energy source. It is a technology that incrementally, but significantly, allows us to make better use of the energy from conventional fossil and non-fossil energy sources. sCO_2 power cycles replace the steam or air of a conventional plant with carbon dioxide (CO_2) at very high pressures and temperatures. CO_2 is a common gas that is abundantly available, non-toxic, and easily handled. Due to the high density, high heat capacity and low viscosity of sCO_2, power plant efficiency gains of 3-5% are easily realized versus conventional steam plants. In industrial waste heat recovery, nuclear, and concentrating solar power, plant efficiency improvements of 10-15% over steam are possible. Waste heat recovery from thousands of currently underutilized energy streams in industry becomes technically feasible and commercially viable. sCO_2 power plants are about 5-10 times smaller than current plants which drastically reduces plant capital costs, reduces footprint requirements, and improves plant grid response. Finally, sCO_2 technology provides a line of sight development plan toward oxy-combustion: A less expensive, higher efficiency, and completely carbon-free emission fossil fuel power plant.

sCO_2 power cycles are on the verge of commercialization and the US is clearly the leader in sCO_2 power cycle technology. A mix of nearly 120 government and industry projects with approximately equal R&D funding of $500M from government and $500M from industry, has allowed moving the technology from the concept stage to functioning plants over a short period of less than 8 years. Several US Department of Energy (DOE) offices, including NETL, NREL, EERE, Nuclear, and ARPA-e, constructively collaborated in this effort. We are now working on a sCO_2 pilot research facility plant called the Supercritical Transformational Electric Power (STEP) program that is designed to help industry address pre-competitive development problems and demonstrate key cycle components. STEP is a $115M program led by the Gas Technology Institute, SwRI, and GE, and co-funded by the DOE with $80M that aims to demonstrate a 10 MW utility scale sCO_2 power plant. The STEP facility will be located at SwRI and is scheduled to be operational by 2020.

The STEP program, as well as, many industry and government funded sCO_2 power cycle technology R&D projects, benefit the US economy not simply through the development of better power plants for domestic and industrial electricity consumers, it also re-enforces the US leadership position in energy systems, power plant technology, and clean electricity. Crosscutting sCO_2 power cycle R&D will result in cheap, reliable, and clean electricity which are major drivers of the US economy.

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Good morning Chairman Smith, Ranking Member Johnson, Chairman Weber, Ranking Member Veasey, Chairman Biggs and Ranking Member Bonamici. My name is Klaus Brun and I am the Machinery Program Director at Southwest Research Institute in San Antonio, Texas. I am honored and pleased to address you today on behalf of Southwest Research Institute.

Southwest Research Institute Background

Southwest Research Institute (SwRI), headquartered in San Antonio, Texas, is one of the oldest and largest independent, nonprofit, applied research and development (R&D) organizations in the United States. Founded in 1947 by businessman Tom Slick, Jr., SwRI provides contract research and development. We are multi-disciplinary problem solvers providing independent, premier services to government and industry clients. Since our inception more than 70 years ago our mission has been to work in the public's best interest and toward the betterment of mankind.

The institute consists of nine technical divisions that offer multidisciplinary, problem-solving services in a variety of areas in engineering and the physical sciences. More than 4,000 projects are active at the institute at any given time. These projects are funded almost equally between the government and commercial sectors. At the close of 2017, the SwRI staff numbered 2,574 employees and total revenue was more than $528 million for the fiscal year. The institute also provided more than $7 million to fund innovative research through its internally sponsored R&D program. SwRI's headquarters - with over 210 buildings - provide more than two million square feet of office and laboratory space on more than 1,250 acres in the heart of San Antonio. SwRI also has technical offices and laboratories in Boulder, Colorado; Ann Arbor, Michigan; Warner-Robins, Georgia; Ogden, Utah; Oklahoma City, Oklahoma; Rockville, Maryland; Minneapolis, Minnesota; Beijing, China; and other locations.

SwRI's research and development is very diverse and ranges from deep sea to deep space, and everything in between. We are currently active participants in several deep space missions including being the principal investigator on the Juno Jupiter mission and the New Horizons Pluto fly-by and Kuiper belt exploration missions. On the other end of the spectrum, SwRI has been involved in the design and testing of the Alvin deep sea submersibles, as well as, the Navy rescue submarine system. We are engaged in a wide range of exciting state-of-the-art research and development programs for the benefit of the US industry and government.

<u>Supercritical Carbon Dioxide Power Cycles</u>

Electricity consumers, both industrial and domestic, always want cheap and reliable energy. Cheap and reliable energy is one of the critical drivers of our economy. The American public cannot afford blackouts and does not want to pay high electricity bills. Over the last 40 to 50 years consumers have also started to demand that our energy is clean to produce and does not pollute our environment.

Today I would like to report on some of the exciting research and development achievements in the area of advanced electricity generation plant technology, specifically the supercritical carbon dioxide (sCO_2) power cycle. The sCO_2 power cycle development has been a major collaborative effort between industry, government, and research institutes to support the US fossil fuel power industry with advanced novel power cycle technology to make electricity cheaper, more reliable, and cleaner.

But first allow me to talk a little about the history of power plants and the importance of sCO_2 power cycles for today's power generation industry. For the last 250 years the majority of fossil-fueled power plants have been using steam and air as the working fluids in their cycle. The venerable steam engine, at least in its basic modern form, was invented by James Watt in 1781 and it, and its successor-derived products, have served us well in producing electricity for industry and consumers. We have come a long way in designing power plants and have driven efficiency up and emissions down. Even 50 years ago the average power plant efficiency was well below 25%. Today's advanced combined-cycle power plants operate near 65% efficiency with ultralow emissions of all criteria pollutants. But technology development never stands still and so now we must pursue the next generation of power plants and power storage to further improve efficiencies and reduce emissions while maintaining reliability for US electricity consumers. The sCO_2 power cycle is not a new energy source. It is a technology that incrementally, but significantly, allows us to make better use of the energy from conventional fossil and non-fossil energy sources.

Nearly 90% of all energy produced in the US comes from thermal power plants. In a thermal power plant energy is converted to electricity by heating steam or air and expanding it across a power turbine. Examples of thermal power plants include all types of coal and natural gas power plants, nuclear power plants, and even concentrating solar power plants. The sCO_2 power cycle replaces the steam or air of a conventional heat engine with carbon dioxide (CO_2) at very high pressures and temperatures. CO_2 is a common gas that is abundantly available, non-toxic, and easily handled. We consume it daily in carbonated soft drinks (and beer) and it is widely used in many industrial processes and consumer products. But CO_2 has thermodynamic properties that, when it is in a supercritical or dense phase state, make it as advantageous as a process fluid for power cycles. Several closed cycle heat engines, including the Cascade, the Allam, the Re-Compression, and the Brun thermodynamic cycles, target these physical properties of sCO_2 to make a more efficient thermal power plant.

There are significant incentives driving the development of this technology for commercial use. Due to the high density, high heat capacity and low viscosity of sCO_2, power plant efficiency gains of 3-5% are easily realized versus conventional steam plants. In some applications, such as industrial waste heat recovery, nuclear, and concentrating solar power, plant efficiency improvements of 10-15% over steam are possible. Waste heat recovery from thousands of currently underutilized energy streams in the manufacturing industry and oil & gas production and transportation becomes technically feasible and commercially viable with sCO_2 technology. Additionally, this results in the footprint of a sCO_2 power cycle being only a fraction of that of conventional plants. We expect sCO_2 power plants to be about 5-10 times smaller than current plants. This drastically reduces plant capital costs, allows for modularity of construction, and even provides the potential for mobile power plants. Also, because of its small size and low thermal mass, a sCO_2 plant can be operated dynamically and provide a fast response to electricity demand and supply changes on a grid with varying alternative - wind and solar - energy inputs. This eliminates one of the major disadvantages of many fossil power plants that can only operate in steady baseload. sCO_2 plants require no water and can easily be sited in arid regions of the US. Finally, sCO_2 technology provides a line of sight development plan toward a less expensive, higher efficiency, and completely carbon emission fossil fuel power plant. For example, using direct-fired pressurized oxy-combustion sCO_2 cycles that are currently being developed, natural gas plants with nearly complete carbon capture and efficiencies equivalent to combined-cycle plants can be achieved.

So why now? The thermodynamic advantages of sCO_2 power cycles have been known since the early nineteen-fifties. But at the time the manufacturing technology, the materials, and the design tools did not exist to produce a sCO_2 power cycle. Using advanced additive manufacturing, high-temperature and high-strength super-alloys, and advanced computational engineering design tools - technologies that have only recently become available - we can now build the complex micro-channel heat exchangers and ultra-high energy density compressors and expanders that are needed for sCO_2 power cycles. These technologies are advancing at a very rapid pace and with the US being the clear technology leader, we can expect significant further benefits and efficiency improvements to power plants in the near future.

In summary, the sCO_2 power cycle does not replace current fossil and non-fossil power plants, it just makes them more efficient and cleaner. Although steam and air cycles will continue to dominate the power generation industry in the foreseeable future, recent developments in materials, manufacturing, and design have led to the development of sCO_2 cycles as an alternative. sCO_2 plants are significantly simpler than typical steam or combined cycle plants, offer a greater power density, a higher efficiency, lower emissions, and most importantly a lower cost of electricity.

Crosscutting R&D and STEP

sCO_2 power cycles are on the verge of commercialization and the US is clearly the leader in sCO_2 power cycle technology. But other countries are trying to catch up and we need to continue to advance this technology to stay ahead. The rapid advancement of technology for the sCO_2 power cycle in the US is the result of a highly successful collaboration between industry, government, national labs, independent labs, and academia. This has been accomplished through industry and government coordinated efforts on focused R&D, cross-cutting initiatives, targeted project funding, and a tight integration of activities of national and private research laboratories, academia, and industry. A mix of nearly 120 government and industry projects with approximately equal R&D funding of $500M from government and $500M from industry, has allowed moving the technology from the concept stage to functioning machinery, subsystems, and plants over a short period of less than 8 years. In a technology area were major advances are usually measured in decades rather than years that is an incredible pace for power plant development. Clearly, this aggressive collaborative R&D approach to rapidly mature an emerging energy technology could serve as a model to advance other highly relevant energy technologies, such as energy storage or oxy-combustion, in the near future.

Several sCO_2 pilot power plants are now being built using both commercial and government funding sources for each application area including fossil fuel, concentrated solar power, and industrial waste heat recovery. Major US manufacturers, equipment suppliers and vendors, and many small startups have been able to develop their own sCO_2 products and systems, greatly benefiting directly and indirectly from government funded efforts. Government funding not only aided in risk reduction during the early concept development stages but also resulted in speeding up the product development cycle and time to market. Clearly this benefits the US public by making higher efficiency and cleaner power generation plants available to the consumer more quickly and at a lower cost.

Several US Department of Energy (DOE) offices constructively collaborated to move sCO_2 power cycle technology forward through a mix of small individual focused and large broad multi-division projects and programs. These offices included DOE NETL, NREL, EERE, Nuclear, and ARPA-e, each funding projects in their specific application area, but all coordinated to provide broad program benefits. One of the benefits is that we are now working on a sCO_2 pilot research facility plant that is designed to help industry address pre-competitive development problems jointly to continue to rapidly advance the technology and to demonstrate key advanced cycle components. This, the largest of the DOE sCO_2 power cycle crosscutting initiatives, is the Supercritical Transformational Electric Power (STEP) program. STEP is a $115M program led by the Gas Technology Institute, SwRI, and GE, and co-funded by the DOE with $80M that aims to demonstrate various configurations of a commercially relevant scale sCO_2 power plant operating up to 715 degrees Celsius firing temperature and 10 MW output power. The STEP facility will be located at SwRI and is scheduled to be operational by 2020. Beyond the primary operational and R&D program targets, STEP will serve as an open-access joint industry R&D facilities for technology developers to test and improve their sCO_2 power plant products. Basically, STEP will first validate the performance improvement predictions of the utility scale sCO_2 cycle technology and then be available to industry, government, and academia as an open reconfigurable R&D facility.

The STEP program, as well as, many industry and government funded sCO_2 power cycle technology R&D projects, benefit the US economy not simply through the development of better power plants for domestic and industrial electricity consumers, it also re-enforces the US leadership position in energy systems, power plant technology, and clean electricity. Ongoing sCO_2 activities drive cutting edge R&D projects with significant global visibility, provide hundreds of high-skills/high-wage jobs, and lead to a continuous education of world-class engineers, scientists, and researchers. Finally, crosscutting sCO_2 power cycle R&D will result in cheap, reliable, and clean electricity which are major drivers of the US economy.

Closing

SwRI is a major US not-for-profit independent R&D institute engaged in the development of advanced power generation and energy storage technologies. We have been an active leader in sCO_2 power cycle technology for the last ten years. During this time we have worked with the DOE, several national labs, universities and many industrial partners including GE, Gas Technology Institute, Aerojet Rocketdyne, Solar Turbines, and a host of others on over 30 sCO_2 related projects. In my opinion, the sCO_2 power cycle collaboration and crosscutting initiative between government, industry, institutes, national labs, and academia is currently one of the most successful cooperative R&D programs in the energy industry. Continued participation by DOE and other government agencies in the STEP program and other sCO_2 power projects will result in major benefits to the US power industry, as well as, US energy technology leadership. Rarely does a new technology emerge that is capable of offering so many solutions. The market potential for sCO_2 plants explains the rapid progress and interest in sCO_2 power.

I sincerely want to thank the US government, its various agencies, and its employees who have and continue to be actively and passionately involved in this very important work. Thank you very much! I am honored to have been invited to talk about this exciting technology to the congressional Subcommittee on Energy and Environment and I look forward to your questions.

Klaus Brun – Short Bio

Dr. Brun is currently the Machinery Program Director at Southwest Research Institute where he leads an organization of more than 60 that focuses on R&D for the energy industry. He is internationally recognized for his expertise in energy systems, power generation, and turbo-machinery. He holds a B.Sc. from the University of Florida and M.Sc. and Ph.D. from the University of Virginia in Mechanical Engineering. His past experience includes positions in engineering, project management, and management at Solar Turbines, General Electric, and Alstom. He holds eight patents, authored over 350 papers, and published three textbooks on energy systems and turbomachinery. Dr. Brun is a Fellow of the ASME and won an R&D 100 award in 2007 for his Semi-Active Valve invention. He also won the ASME Industrial Gas Turbine Award in 2016 and ASME Oil & Gas Committee Best Paper/Tutorial awards in 1998, 2000, 2005, 2009, 2010, 2012, 2014, 2016, and 2017. Dr. Brun organized and chaired numerous international conferences including the International sCO2 Symposium 2016, Turbo Expo 2012, and the Oil & Gas Lecture Series 2016-2018. Dr. Brun is the past chair of the ASME-IGTI Board of Directors, the ASME Oil & Gas Applications Committee, and ASME sCO2 Power Cycle Committee. He is also a member of the API 616 Task Force, the ASME PTC-10 task force, the Asia Turbomachinery Symposiums Committee, the Fan Conference Advisory Committee, and Supercritical CO2 Symposium Advisory Committee. Dr. Brun is the past Editor of Gas Turbine News and currently the Executive Correspondent of Turbomachinery International Magazine and Associate Editor of the ASME Journal of Gas Turbines for Power.