ORIGINAL ARTICLE

Space Commodities Futures Trading Exchange: Adapting Terrestrial Market Mechanisms to Grow a Sustainable Space Economy

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ABSTRACT

This article describes a formalized commodities exchange that lets all market participants in the space economy better visualize and predict market opportunities and risks, by enabling them to trade standardized and reliable space commodities to be designed, supplied, or necessary in the near future. Such an exchange would enable commercial and government organizations to identify quantifiable surpluses, gaps, valuations, and destinations for space commodities that economically and scientifically achieve and sustain their space exploration and development goals faster, cheaper, and safer. Such organized market transaction data and analysis would also let potential suppliers better understand market demand and justify capital investment and valuation. Inspired by the commodities futures trading exchanges that exist today terrestrially, an adaptation is suggested through which a similar trading exchange would be established to support the emerging space economy by offering five groups of space commodities, including futures contracts for standardized in-space services to financial derivatives for risk transfer and liquidity. This article will also consider how growth of the space economy could be slowed or investments misallocated in the absence of such a trading exchange for space commodities.

Keywords: futures market, space economy, space resources, space commodities, space commodity exchange, space commodities market

INTRODUCTION

Government Road Maps for Space Exploration

Over the past decade, space agencies of the developed nations have debated and proposed road maps for the exploration of space, in phases defined by destinations, such as the Moon, Mars, Near Earth Asteroids, and the technical and financial challenges involved in reaching these destinations.[1–5] NASA updates its space exploration road maps on a regular basis to include recent scientific and technology advances that could impact future missions, and receives regular academic, commercial, and public feedback on the sufficiency and boldness of such road maps.[6,7] The Federal Aviation Administration (FAA) also updates its commercial launch forecasts, road maps, and business models.[8] The European Space Agency (ESA) continually reviews and seeks to harmonize its road maps.[9] The International Space Exploration Coordination Group (ISECG) is a collaboration of 14 space agencies, including NASA and ESA, organized to coordinate their space exploration plans as an integrated Global Exploration Road Map.[3] Government road maps have focused mainly on the exploration of space.

On the Commercial Frontier of the Space Economy

To date, no common road map exists for the development and operation of the space economy nor how to collaboratively build the space economy commercially, technically, legally, or financially.

"Space economy" as used herein refers to the economy that builds, operates, exchanges, and finances assets that improve or use of the functional value of space exploration, discovery, and commercialization. This definition upgrades the traditional definition of the "space economy" as a nominal percentage of the gross domestic product of a national economy generated through investments in facilities and employment on Earth to build and operate assets involved in space activities.[10–12]

Commercial New Space leaders have their own vision for space development and work off their own road maps, developing the infrastructure and services they see as critical.[13,14] Founders and angel investors in companies such as SpaceX (Elon Musk) and Blue Origin (Jeff Bezos) providing reusable launch services, Virgin Galactic (Sir Richard Branson) providing space tourism, Bigelow Aerospace (Robert Bigelow) for habitats in space, Planetary Resources (Eric Schmidt, Larry Page, and Ross Perot, Jr.) mining asteroids and others aim to dominate in offering key assets and services.

A robust space economy requires growing the market for space products and services, where, for example, investments in launch services to the Moon would be proportional to the lunar development activities requiring launch, orbit, and return from the Moon back to Earth, or for operating on the Moon, with lunar minerals by building other assets.

Entrepreneurship, open market competition, and innovation jump-start and revive economies and disrupt entrenched corporate and other interests. However, commercial competitors providing high technology goods and services initially resist efforts to coordinate their interoperability, to grow demand for, and revenues from bespoke customization services that specifically fit the demands of a technically sophisticated and experienced customer base.

Without a shared road map and commercially viable interoperability standards for the shopping list of items needed to successfully get to, operate in, and return from or travel across space, commercial space customers will incur significant costs, delays, and uncertainties in achieving situational awareness regarding the availability of required goods and services that can be provided by the rapidly expanding space economy.

SPACE COMMODITIES

Within the span of a decade, average U.S. households went from having no computers to having multiple computers and carrying smartphones in their pockets. Commodification has meant standardized chipsets, routers, cameras, programming languages, and other technological assets that adapt to an infinite variety of uses in the home, at work, in vehicles, in appliances, on lamp posts, and nearly everywhere else—in occupied and remote areas on Earth. As a catalyst for economic growth, access to advanced information, medical[15] and other technologies increasingly defines national, regional, and individual options for success and equity.[16–18]

In space, what would or should be traded as a "commodity?"[19] The question will prompt a sequence of iterative answers, moving step by step to match the space economy's commercial growth and technological evolution.

Bandwidth for data transmission will be a space commodity, based on a packet size of data transferred between or across defined locations, at a minimum speed, and with an agreed upon level of quality and cyber security to assure safety and integrity of the unaltered data as transmitted and received. Image and remote sensing information storage and processing, secure digital identity and documentation, and launch and cargo services in Low Earth Orbit (LEO) are already moving toward commodity definition, provisioning, and procurement.

Water is likely to be one of the first space commodities derived *in situ*, when it is available in a standard unit of quality and quantity for use in a specific orbit or off-Earth destination, for a defined period of time. Water for industrial use as fuel (hydrogen and oxygen) or as binding agent for building materials would differ in quality and quality unit from water intended for human consumption or for medical, pharmaceutical, or agricultural use, thus defining multiple definitions for water traded as commodity.

Rare earth metals used in manufacturing on Earth likewise will be commodities to be mined, recycled, and used in space.[20] Platinum group metals could also potentially be traded when the extraction, processing, and transportation cost are reduced to the appropriate level.

The compendium of space commodities will grow dynamically as new sources of the materials are found and successive missions are planned to align around common destinations, routes, and technologies in the space economy. There is a parable told in law school, that there were two towns. In the first, a freshly minted lawyer hung out his shingle and opened his law practice, and waited for clients. He was about to close shop, until another lawyer showed up across the street. The two lawyers made boatloads of money over their prosperous careers, representing townspeople in their varying transactions and occasional disputes. Like the two lawyers, having complementary commodity services available at optimized destinations in space will let their providers thrive, by forming an economically interdependent supply chain.

Standardized specifications for interoperable space commodities will need to be verifiable, and disputes mediated to reduce risk to space business models. (For background on the legal and organizational challenges of space commodity mining, ownership, exchange, and use, see the cited reference.[21])

To focus imagination and debate on what characteristics define a "space commodity," consider five categories of terrestrial commodities (the "Five Buckets of Commodities"):

(1) *Raw Materials* that are found *in situ* and are suitable for processing into higher valued goods and services.

(2) *Processed or Refined Goods* specified as conforming to a measurable quality or other criteria.
(3) *Services* that are provided using raw materials, processed or refined goods, or other services.
(4) *Contractual or Legally Enforceable Rights* to acquire, supply, or use raw materials, processed or refined goods, or services, immediately or at a specified date and location, in the future.
(5) *Financial Rights*, held as investor, lender, or other virtual rights holder, derived from ownership or pledge of other space commodities.

Applying this framework yields distinctive categories of space commodities mapped as *Table 1*.

The Five Buckets framework focused definitions of a "space commodity" on its distinct origin or function, rather than on specifying a specific technology standard through which to process and produce the commodity. Domain experts will evolve numerous and competing space-borne technology and process standards for producing space commodities. The dual nature of a market structure (commodities defined to be traded) and a technology infrastructure (how the commodities are produced and offered) is designed to be agile and flexible in anticipating the growth of a healthy space economy.

On Earth, humankind uses more in resources than nature produces. Terrestrial mining, advancing its responsible processes, and the reuse of mined materials and their by-products, have been identified as opportunities for mitigating natural habitat loss, climate change, waste, energy use, and the economic and social inequality that results.[22–24]

Off Earth, in space, the potential to mine, refine, manufacture, recycle, and repurpose will be vital to the economic and physical survival of the space explorers and entrepreneurs. Balancing biological, chemical, material, and economic elements will be needed to produce a vibrant closed-loop ecosystem. Commodities created for this circular and sustainable economy will be much more valuable than commodities produced for single use or single missions.

Table 1. Examples of Space Commodities

Space Commodity Category	Examples of Space Commodities
Raw materials	Regolith, rock, mineral, or natural substance
Processed goods	Naturally occurring process such as biological or agricultural plant, food, waste-repurposing/waste-to-energy, or other process
	Human-engineered process such as producing water from lunar rock or hydrogen from lunar water
In-space services	Human-engineered processes for • launch or other transportation to move cargo or personnel to or from space • robotic exploration or repair of in-space assets or objects • temporary physical storage or habitation with life support services • energy, telecommunications bandwidth, computational services for acquisition, storage, analysis, and manipulation of data (ICT)
Contractual rights	Spot, Future and Forward Contracts (described in section Contracts Used to Transfer Future Interests in Assets and Their Supply, Demand, and Price) to own or take physical delivery of another space commodity
Financial rights	Future, forward, derivative and other contracts transferring the right to participate in changes in value of another space commodity

COMMODITIES TRADING 101

Commodities trading transforms (1) physical goods and services into (2) standardized contracts, and transforms (3) capital available today into (4) contractual rights to take delivery of future goods or their future value.

Commodities for current use (spot market) differ in value, variety, quality, and price from commodities to be provided at a fixed date in the future.

Commodities that begin as physical goods, when specified for delivery in a standard contract, become virtual commodities, since the contract can be resold and transferred to another buyer, thus becoming a tradeable asset that derives from, but exists independently from, the physical commodity mined, grown, or processed.

When the contract rights or the prices of the contract rights to acquire future commodities are bundled together in an index, the value of the commodities index becomes a distinct commodity, as a derivative of the underlying commodities' price and supply movements. (For a general primer on commodities, see the cited reference.[25])

The new space economy produces goods and services available for future delivery and use.

HISTORICAL PRECEDENTS FOR A SPACE COMMODITY MARKET

Commodities trading in space can follow the precedent of terrestrial commodities in developing an adaptive exchange structure.

Historical Precedents in Agricultural Commodity Markets

Commodity markets date back to Ancient Greek and Roman times, where grain and its seasonal growth, quality, place of harvest, and supply routes led to government price controls, duties, and regulation.[26(pp. 47–74),27]

Major milestones in the last five centuries of commodity market development include the following:

- 1531 Bourse in Antwerp opens as the first building designed for the trading of commodity and financial futures. The word "bourse" pays homage to an inn run by the family Van der Beurze in the Belgian town of Bruges, where 15th century merchants met to conduct financial affairs. The Antwerp Bourse closed on December 31, 1997, as a result of merger with the Brussels Bourse.[28]
- 1571 Royal Exchange opened in London[29]
- 1715 Dojima Rice Exchange opened in Osaka, Japan[30]
- 1848 Chicago Board of Trade (CBOT) organized[31]
- 1864 CBOT listed the first standardized "exchange traded" forward contracts called *futures contracts*[32]
- 1877 London Metal Market and Exchange Company (London Metal Exchange) opened.

Agricultural commodities offer a variety of challenges in grading consistency, quality, and shelf-life/storage. To the casual observer, an orange is an orange, and a bale of cotton is just cotton. However, the farmers, food processors, commodities brokers, and regulators have very different and much more nuanced opinions. The U.S. Department of Agriculture (USDA) defines eight grades[33] and 20 quality and size ranges[34,35] for oranges, and differentiates cotton by four major types (Pima, Calibration, Instrument, and Upland), and within each cotton type a variety of colors, strengths, and conditions.[36,37]

Given the variety and grades of agricultural commodities, futures contracts use benchmark commodity prices to protect suppliers and users of the commodity against price, availability, and currency risks. The benchmark commodity is typically in plentiful demand or historically widely traded by end product or value-added manufacturers. Thus, spot and futures prices of other types, grades, and quality of a commodity can be quoted as a spread from the benchmark commodity's price.

Imagine Farmer Jones grows oranges and Farmer Smith grows cotton. Only at the end of harvest season do the farmers know the exact quantity, quality, and yield for each type of orange and cotton grown. Seasonal weather patterns, insect infestation, water shortages, and other factors affecting the farmers' crop yields can be insured under government-sponsored or -subsidized insurance programs.[38]

Because prices for various types of oranges move in a band in relation to the highest quality (U.S. Fancy) grade of oranges, and for cotton in relation to American Pima, orange and cotton farmers, respectively, hedge the price for their harvest by buying futures contracts pegged to U.S. Fancy oranges or American Pima cotton for delivery at a date after the harvest season. Thus, Farmer Jones can use the fluctuation of the price of U.S. Fancy oranges to compensate for the market's relative demand for his crop of oranges, and Farmer Smith can hedge the market price for his cotton based on fluctuations in the price of American Pima cotton.[39] In practice, the farmers' roles may be delegated to, or assumed by, nonfarmer wholesalers, warehouse operators, or other intermediaries, but the commodity markets hedging rationale remains essentially the same for a prudent portion of the farmers' expected output.[40–42] In this scenario, Farmers Jones and Smith are participating in the agricultural commodities markets in two roles: directly (by contracting to sell their crop of oranges and cotton) and derivatively (by buying a financial futures contract based on the benchmark grade of orange or cotton). (For a primer on agricultural commodities hedging with quantitative examples, see the cited references.[43–46])

Today, Chicago Mercantile Exchange (CME or the "Merc"), the CBOT's successor,[47] trades agricultural, industrial, and other physical commodities, as well as financial derivatives and futures contracts derived therefrom. The majority of futures contracts on the Merc involve financial futures contracts hedging inflation, interest rate, and currency risks.

Historical Precedents in Rare Minerals Commodity Markets

Standardizing the purity and grading of rare natural and synthetic minerals presents a specialized challenge, given that producers, refiners, dealers, and their lenders and insurers need to invest in significant mining, refining, and distribution infrastructure in advance of the markets for customers wishing to purchase the mineral for specific applications. A diamond used in industrial grinding and polishing is necessarily of different type, weight, clarity, color, and other characteristics than the gemological diamonds in Cartier, Tiffany, and Van Cleef & Arpels Fifth Avenue jewel's showcases.[48,49]

On September 17, 1890, The Vereniging Beurs voor den Diamanthandel (Association Bourse for the Diamond Trade) began operations and launched a network of similar diamond exchanges globally.[50] In 1904, the Dutch Diamond Bourse opened in Antwerp to offer diamond traders, polishers, and financiers more security than conducting their affairs in a local café.[51] In 1911, The Vereniging Beurs voor den Diamanthandel opened a specialized building on Weesperstraat in Amsterdam designed for their Diamond Bourse operations.

Initially, in 1907, with the establishment of the International Federation of Diamond Bourses, and then after World War II in 1947 with the establishment of the World Federation of Diamond Bourses, the standards defining the commodity grading of diamonds and the operations of bourses for commodity exchange became globally consistent.[52,53]

Diamonds and other commodities provide a means to store value without using banks or fiat currencies. As currency-substitute, high-value commodities can be misappropriated if steps to protect industry producers, dealers, and customers are nonexistent or ineffectual. The Third Reich in Nazi Germany attempted to control the world diamond market and its methods of exchange, threatening Jewish and non-Jewish participants in diamond exchange operations in Holland, and the portion of Dutch tax revenues from diamond industry sources.[54]

In response to United Nations Security Council and General Assembly resolutions, the World Diamond Council was established in 2000 to represent the diamond industry in developing and assisting in government enforcement of standards for certifying diamonds traded among the major producer, bourse, and customer countries.[55] Known as the "Kimberley Process Certificate Scheme," the industry is addressing country of origin and trafficking in conflict or blood diamonds to control and eliminate a large range of misuse of diamonds as currency for illicit activities, including money laundering, terrorism, and other criminal behaviors.[56]

Historical Precedents for Commodity Standards in the Growth of the American Railroads to Transport the Industrial Revolution

As the Industrial Revolution redefined mid-19th century economics, massive investments grew America's railroads as the infrastructure to provide cheap transcontinental transportation of goods from farm and quarry, to factory, to warehouse, to customer, and the labor, housing, and other assets needed to support the urban centers surrounding the railroad, factories, and marketplaces.[57]

"The industrial revolution opened a new chapter in the history of material specifications. Locomotive builders, steel rail producers, and steam engine builders who used revolutionary new materials such as Bessemer steel could no longer rely on craft experiences of centuries past. The new materials and techniques invented during this period required new technical expertise. Moreover, manufacturers encountered numerous quality problems in end products such as steel rails because suppliers furnished inferior materials. American rails were so poorly-made, in fact, that many railroad companies preferred British imports, which were more expensive but reliable. To avoid such problems, some manufacturers issued detailed descriptions of material to ensure that their supplies met certain quality standards. For example, when a federal arsenal ordered gun steel from a steel mill, the contract included several pages of specifications detailing chemical composition and physical characteristics. The federal government also asked the steel makers to take a sample from each steel batch which was then subjected to a few simple tests determining its tensile strength and elasticity. To perform quality checks, American steel companies used new testing equipment such as the Riehle steel tester or a version of Tinius Olsen's Little Giant, which were used to determine tensile strength."[58]

America's railroads catalyzed standardizing the chemical composition of steel and other materials used in rails, locomotive engines, and other infrastructure, as the American Standards Testing Materials (ASTM) organization's history recites (see Appendix 1).

Historical Precedents in Chemical Commodity Markets

The standards for chemical commodities and their formulations are updated and controlled through subject-matter experts in industry and government, where purity is graded to safeguard the intended use in medical, experimental, physical, or other applications.[59,60] How chemical standards were historically set and updated based on evolving technology and process improvements suggests the supply chains that might be replicated for chemical compounds as commodities in the space economy.[61(pp. 480–492),62]

Why Some Futures Markets Succeed and Others Fail

Except during extreme economic events (declaration of war, depression, regional natural disaster or political uncertainty), commodities markets thrive on risk, and transferring risk for a price and term among market participants. During normal maturation of commodities markets, price and supply volatility are risks that grow and feed healthy futures markets.[63,64] Market participants who want to off-load risk to others, and counterparties who want to diversify or speculate on the risks, find the volatility of price and availability, defined for standard or benchmarked commodities, to reduce their overall exposures to market demand and supply forces. In this regard, government wholesale price controls or other interventions, if too rigid,[65] can limit the healthy growth of emerging commodities markets.[66(pp. 237–271)]

Major Commodities Markets Today

The global reach of terrestrial businesses and government activities rely on major commodities markets that can be grouped as follows[67–69]:

- Agriculture and Fertilizers
- Energy—Oil, Coal, Natural Gas, Electricity

- Environmental Emission Caps
- Foreign Currency Exchange
- Freight and Other Transportation Services
- Metals and Minerals
- Weather Risk
- Financial Futures in one or more of such commodities.

Given the diversity of terrestrial processing and supply chains, other commodities markets and exchanges supplement the major classification schemes.[70,71]

GOVERNMENT PROCUREMENT SAVINGS VIA COMMODITY ACQUISITION STRATEGIES

In peacetime and during times of war,[72] government procurement needs from domestic and global supply chains led to additional industry and government commodities standardization and testing organizations to accelerate the quality, availability, and price competitiveness of American goods and services. Government agencies, and the private sector's standards-setting organizations (such as ASTM) responded with definitions for pharmaceuticals, concrete and a myriad of supplies for government operations and programs.

Since 2005, federal procurement strategy has sought cost savings through bulk procurement mechanisms such as the Federal Strategic Sourcing Initiatives (FSSIs) under the auspices of the Office of Management and Budget, the Office of Federal Procurement Policy, the General Services Administration (GSA), and the Department of Treasury (Treasury) and with the input from the Leadership Council of the seven agencies with the largest procurement budgets, of which NASA is a member.[73] Through the FSSI approach, procurement objectives for government programs and their government contractors are reframed holistically, aggregated, and the optimum procurement mechanism is used.

The culture of federal agencies, the nature of agency trust in transformative procurement processes, and their results vary markedly, and significantly influence the share of potential savings that are actually achieved.[74,75] For new markets, without legacy procurement methods or entrenched vendors where federal procurement activities are in their infancy or are most malleable, one could imagine instilling culture and trust in relying on commodity procurements early on to improve the quality and savings enjoyed by the federal government, while increasing the marketplace's supply of commodity goods for private sector use.

IMAGINE A SPACE ECONOMY WITHOUT A COMMODITIES MARKETPLACE

A space economy is forming organically, with the intervention of finance, technology, start-up, and other participants. Nothing in the five major United Nations Space Treaties or in any other multinational space agreement provides for (or expressly subsumes authority for) a space commodities exchange, space commodity standardization, or other features of an organized marketplace.[76]

Is a commodities exchange essential for the space economy to form rationally around achievable goals, and to function safely, efficiently and equitably, are space commodities utility goods, best provided by regulated monopoly or oligopoly enterprises, where rents and other charges for the commodity are set by government fiat, and are space commodities like open data that minimize the proprietary cost of bespoke requirement specification, acquisition, waste, and risk?[77–79] If open data are the international norm for access to science on Earth, are access to space commodities an essential corollary to democratize scientific exploration of space?[80]

The scope of economic questions, analyses, and outcomes involved in commercializing space exploration and colonization is worthy of textbook treatment and testing through game theory machine-learning modeling.[81,82(pp. 629–644)]

Given the high human, financial, and scientific risks of failure in new technologies in unknown environments at great distances, proprietary chemical, physical, or virtual connections between space goods and services could be life and mission threatening.

Imagine the air locks, air, water, fuel, energy, sanitation, and other chemical and mechanical fittings needed to access and colonize the Moon or Mars. Now imagine that instead of the ubiquitous electric wall outlet, each mission installs and has extension cords only for its national wall socket or hoses for its own plumbing fittings. Imagine each mission uses a chemical formulary through which its human, animal, and plant life support and maintenance design requirements differ and even threaten coexistence with subsequent missions nearby.[83] Proprietary standards for communications, geospatial and technical data exchange, software access permissions, technical libraries, and other essential information infrastructure would add significant human and mission risk, without concomitant redundancy or standby resiliency benefits.

Such nonstandardization of essential space commodities would frustrate and delay the natural economies of scale that commodified markets enjoy. With the additional risks of noninteroperable commodities, missions would continue to incur high insurance and commodity redundancy costs. Proprietary standards, by design or in their practical operation, limit the pace and scope of collaborations available to grow the space economy.

LESSONS FROM COMMODITY MARKET OPERATIONS ON EARTH

The 2008 financial crisis caused central bankers and commodity market regulators to reevaluate how frailties in commodity markets threaten national quality of life. HM Treasury has identified multiple threats,[84(p. 57)] including

- *Widespread Threats*: Volatility of commodity prices causes widespread social, economic, political, and environmental impacts.
- *Social Threats*: Rising commodity prices contribute to inequality, poverty, and hit the poorest nations and neighborhoods the hardest.
- *Macroeconomic Threats*: Rising commodity prices add to inflation, trade imbalances, and government deficits.
- *Geopolitical Threats*: Commodity price and distribution issues destabilize governments and result in political instability, migration, and other threats as citizens question the legitimacy of government services and management.
- *Environmental Threats*: Commodities mined or farmed without adequate regard for natural capital replenishment and stewardship threaten global and local climate and resources.

Space commodity providers and their supply chains would be prudent to assure that the lessons of operating reliable commodities markets on Earth are considered in engineer fault-resilient commodities pricing and distribution systems in space.

LESSONS FROM BUSINESS TO BUSINESS SUPPLY CHAIN PLATFORMS

As the aerospace, automotive, consumer electronics, and other industries have discovered, components made by highly specialized small- to medium-sized enterprises offer the semifinished goods that can accelerate design, fabricate, and assemble into complex high-value goods, such as aircraft, cars, smartphones, and even real estate. The complexity of building modern technology requires supply chains that have the flexibility and variety to reliably manufacture and deliver standardized components.[85]

The Exostar cloud-based online market for managing the aeronautics industry's supply chain provides a valuable precedent for understanding the financial, logistical, cyber, and qualitative benefits of organizing a platform for trading in space commodities.[86,87(pp. 82–90)]

COMMON GOALS THAT DRIVE MARKETS AND PROTECT MARKET PARTICIPANTS

A key theory of market-based economies assumes that they are efficient, egalitarian, and persistently so. The efficient market hypothesis assumes that (1) there are no transaction costs, (2) information is readily accessible to all market participants, and (3) all market participants act rationally in their own interest, and all share rational expectations as to future prices that will prevail in the market.[88(p. 902)] While the equity, transparency, and fairness of markets in practice rarely achieve such theoretical efficiencies, their founders frequently strive to raise the bar, aiming higher, spurred by litigation, regulation, and market forces.[89]

Commodities exchanges bring market participants together to achieve seven common goals:

(1) Reduce the volatility of prices for the commodity.
(2) Match current and future supply and demand for the commodity to avoid shortages and oversupply.
(3) Standardize the commodity's unit of exchange, seasonal delivery schedule, and other quality assurance factors.
(4) Standardize the contractual and transactional steps to buy, sell, pledge, and trade in the commodity in bulk for wholesale purposes.
(5) Monitor the health of the commodities marketplace and the capacity to respond to internal and external shocks.
(6) Mediate and reduce disputes among market participants.
(7) Reduce counterparty risk, since the commodities exchange and the financial and reputation assets stand behind fulfillment of the futures contract.

Bottom line, commodities exchanges offer *liquidity* (via standardized commodity definitions and contracts) and *risk-transfer services* (derivatives of future events).

Take this practical example: "If person A contracts with person B, he faces the risk that person B will renege on the contract. That risk may outweigh the benefits of writing the contract. In a futures market, though, the risk of nonpayment or performance (counterparty risk) of person B is replaced with the counterparty risk of the futures exchange (which is expected to be far less than that of a random individual). The exchange replaces the bilateral contract between person A and person B with two contracts: one between person A and the futures exchange and one between person B and the futures exchange. If B goes bankrupt, person A is not directly harmed, because he has a contract with the commodities exchange. The exchange also requires collateral from person A and person B" (personal communication; unofficial conversation with senior commodities futures exchange regulator who requested anonymity, June 1, 2017).

The common goals driving market function create industry, regulatory and third-party standards, organizational legitimacy, and processes for adopting, enforcing, and easing the transactional authentication and burden of compliance.

HOW PHYSICAL, CONTRACTUAL, AND VIRTUAL COMMODITIES BECOME FINANCIAL DERIVATIVES

Much of the financial engineering on "Wall Street" consists of pledging the future right to (1) acquire ownership or use of a physical commodity, or (2) receive the financial appreciation or rents of a physical commodity.

Technology has changed how financial engineering occurs. With the automated creation, borrowing, pooling, and trading of securities, commodities investors (including speculators) use machine-learning algorithms to improve the timing of trades and the short- and long-term horizons used to forecast commodity portfolio returns.[90]

Imagine that a company offers lunar launch services for inanimate cargo (physical, but not human, animal, or biological), during the Gregorian calendar year 2025, based on a standard payload (kilogram weight) and physical container size (cubic meters), from a physical launch site on Earth to a destination on the Moon, for a fixed price. The contract for launch services is issued in 2017—8 years before the date for the transportation service. In this regard, the contract resembles a financial option—a financial derivative of the actual launch service.

Between 2017 and 2025, the market value of the launch contract can appreciate or depreciate based on how the space commodities markets perceive and price factors such as the supply of competing lunar launch services, the improvement in space technology, the additional value of operating in that location on the Moon, the reduction in government spaceflight permits to land on the Moon, and the greater certainty of property rights on the Moon.

Future lunar launch services as a commodity future resemble terrestrial commodities that are fulfilled by physical delivery on standardized terms.

As the CFTC explains:

- "A commodity futures contract is an agreement to buy or sell a particular commodity at a future date.
- The price and the amount of the commodity are fixed at the time of the agreement.
- Most contracts contemplate that the agreement will be fulfilled by actual delivery of the commodity.
- Some contracts allow cash settlement in lieu of delivery.
- Most contracts are liquidated before the delivery date.
- A commodity futures option gives the purchaser the right to buy or sell a particular futures contract at a future date for a particular price.

With limited exceptions, commodity futures and options must be traded through an exchange by persons and firms who are registered with the CFTC."[91]

Once the certainty of a physical commodity or a virtual commodity (such as an interest rate or currency rate future) is defined, the holder of that commodity contract has the ability to readily sell and pledge the contract, increasing the contract parties' liquidity and financial agility. Space suppliers and space customers can use commodity-linked liquidity to navigate fluctuations in payments of accounts receivable, corporate business line focus, and other conditions.

CONTRACTS USED TO TRANSFER FUTURE INTERESTS IN ASSETS AND THEIR SUPPLY, DEMAND, AND PRICE

The historical needs of producers and users of physical commodities as contrasted with investors and speculators concerned with market demand, supply, and pricing of the commodities have led to four major types of contracts summarized below[92–94]:

- *Forward Contracts* require physical delivery of the underlying asset at a later time for a set price. Due to the specifics of handling the physical asset, the parties negotiate a bespoke contract, and the contract therefore is not tradeable on a centralized exchange. The parties (or their assignees) exchange goods for the purchase price at the future settlement date. Due to the bespoke, nonstandard nature of the contract, forwards are either not traded or are traded on a limited basis on an over the counter exchange.
- *Futures Contract*s involve a promise to deliver either (1) the underlying asset at a future time or (2) an equivalent amount of money to acquire the asset at that time. Futures contracts are written in standard form and trade on regulated exchanges. Futures contracts come in many forms. A futures contract could agree to deliver a physical commodity (soybeans or wheat) at a specific warehouse, or as an interest rate futures could agree to deliver a U.S. Treasury note of a certain interest rate and term. During the term of the futures contract, funds would be exchanged between the parties as the spot price moves.
- *Swaps Contracts* are typically used to set a fixed exchange rate between two currencies, for example, U.S. Dollars ($) and U.K. Pounds (£) to be settled at a fixed time in the future. Swaps are useful in supply chain and project finance where the costs of goods produced in multiple foreign countries must be hedged to protect the profit of the manufacturer or assembler of finished goods.
- *Options Contracts* protect the maximum price in the future that would be required to be paid to acquire the underlying asset or the minimum price that would be

received for selling that asset. The option only has value if at the future time for delivery, the price has exceeded or fallen, respectively, relative to the "strike price" set originally. Options are regulated like swaps.

Derivative contracts' key features are highlighted in *Table 2*.[95]

Such contracts capture the parties' reciprocal predictions of future supply and price, colloquially known as a party going "long" or "short." The long position holder buys the contract, to acquire the flexibility of taking physical delivery of the underlying asset or being paid by the counterparty (who holds the short position) to extinguish the contract at a price that permits acquiring the underlying asset. Contracts traded on a registered exchange have the additional advantage of the exchange's enforcement mechanisms as a means to reduce risks of nonpayment or nondelivery, beyond the collateral and contractual remedies available to the nondefaulting party.

COMMODITY FUTURES TRADING COMMISSION AND THE MARKETS IT OVERSEES

The CFTC oversees trading activities for commodities ranging from naturally grown (agricultural and livestock), to mined and processed materials (rare metals), to commodity-related, financially engineered contracts (futures, derivatives, and indexes thereof).

CFTC's statutory authority stems from the Commodity Exchange Act, in which

> "The term 'commodity' means wheat, cotton, rice, corn, oats, barley, rye, flaxseed, grain sorghums, mill feeds, butter, eggs, Solanum tuberosum (Irish potatoes), wool, wool tops, fats and oils (including lard, tallow, cottonseed oil, peanut oil, soybean oil, and all other fats and oils), cottonseed meal, cottonseed, peanuts, soybeans, soybean meal, livestock, livestock products, and frozen concentrated orange juice, and all other goods and articles, … ***and all services, rights, and interests … in which contracts for future delivery are presently or in the future dealt in.*** " [Emphasis supplied].[96]

The CFTC does not regulate trading in all-natural capital, such as local land use and water rights, or carbon pollution allowances. Nor does the CFTC regulate the operation, closure, remediation, and reclamation of mines on federal, state, or private lands. The U.S. Department of the Interior's Office of Surface Mining Reclamation and Enforcement shares jurisdiction with the states over coal mining operations under 30 USC Chapter 25 on Surface Mining Control and Reclamation.[97,98]

The CFTC specializes in assuring the smooth functioning of the markets for trading and investing in the commodities within its jurisdiction.

Most importantly, CFTC does not regulate forward contracts, that is, for physical delivery of the underlying asset.

Depending on the structure, market, and parties, a commodity futures contract and a financial index thereof can span the jurisdiction of the CFTC and the Securities and Exchange Commission (SEC), which jurisdictional oversight was further delineated in the years following the 2008 financial crisis, through the Dodd–Frank Act and successor legislation. For instance, contrast *Jurisdiction of the CFTC* 7 USC Section (a),[99] with *Definition of Excluded Commodity* 7 USC Section 1a (19).[100]

HOW THE CFTC REGISTERS EXISTING AND NEW COMMODITIES MARKETS

Pursuant to 17 CFR Part 38, the CFTC registers boards of trade as designated contracts markets (DCMs) to manage the definition, clearance, exchange, and enforcement of contracts for specific commodities (physical, financial, virtual).[101] Pursuant to the Dodd–Frank Wall Street Reform and Consumer Protection Act of 2010, Public Law 111–203, CFTC removed the exemptions for boards of trade and commercial markets, and reregistered them as DCMs, part of the overall post-2008 financial system regulatory reform process.[102,103(p.80572)]

Numerous DCMs have been registered, of which a fraction remains in operation.[104]

Table 2. Types of Futures Contracts

Type of Contract	Forward	Future	Swap	Option
Asset physically delivered?	Yes	Optional	No	Optional
Standard contract?	No	Yes	Yes	Yes
Trade on exchange?	Over the counter, potentially	Yes	Yes	Yes
Examples of use	Almost any asset	Agricultural and mineral commodities	Interest rates, foreign currencies	Almost any asset

The CFTC is responsible for financial technology innovations under its regulatory authority.[105,106] In 2015 and 2016, CFTC ordered two early bitcoin (cryptocurrency) exchanges to cease operations.[107,108] Subsequently, applications for DCM registration of two cryptocurrency exchanges were filed with CFTC, specifically, Bitnominal Exchange LLC and BCause LLC.[109]

Rather than being a rigid market impediment, the CFTC has overseen the marketplace to register, de-register, and merge DCMs to maintain the vitality of commodity trade and trade finance.

An application for a Space Commodities Futures Trading Exchange would be submitted to the CFTC on the DCM form available online.[110,111]

HOW THE CFTC LICENSES EXISTING AND NEW DERIVATIVES CLEARING ORGANIZATIONS

The risks of commodity transactions and derivative contracts based on such transactions require participants that are creditworthy and that can credit enhance their payment and performance of trading obligations. A *derivatives clearing organization* (DCO) provides clearing services or arrangements that mutualize or transfer credit risk among participants.[112,113] An application to establish and operate a DCO would be submitted to the CFTC on the DCO form available online.[114,115] Like banks, DCOs are stress tested by the CFTC to simulate macroeconomic and systemic risks that the DCO network and participants might face.[116]

INTERNATIONAL COMMODITIES MARKETS AND HOW THEY SUPPLEMENT STATUTORY GAPS THROUGH EFFICIENT OPERATIONS

National commodities markets[117] and their regulatory structures reflect each country's unique agricultural and industrial economic development periods. National markets and their regulation may be increasingly challenged and inadequate to oversee agricultural and mined commodities that are cultivated, shipped, warehoused, traded, reprocessed, owned by investors, financed, hedged, and taxed by global supply chains, cultural appetites for seasonal consumption and logistics.

As financial technology has permitted linking trading activity through business hours and after-hours in all relevant time zones, the mechanical apparatus and rationale for separate national or regional commodities markets are yielding, as commodities markets consolidate on common trading platforms or operate by shared market technology providers.[118–122]

Computable (also called smart) contract trade creation and distributed ledger trade clearing technologies (commonly called blockchain) together with machine-learning algorithms for matching trades and patterns in data supplied by the ubiquity of Internet of Things (IoT) sensors, remote and drone imagery, and big data accessible and analyzed via cloud computing will improve markets' forecasts of the rate and quality of commodity being produced, warehoused, consumed, and hedged.[123(p.629),124–128] Such technological advances will accelerate the speed and globalization of commodities market activity, nationally and multinationally.

ROAD MAP FOR FORMING A SPACE COMMODITIES EXCHANGE

With standardization and stability of the emerging space economy in mind ("Introduction" and "Space Commodities" sections), with ample historical and regulatory precedent ("Commodities Trading 101" to "Government Procurement Savings via Commodity Acquisition Strategies" sections), and to achieve the tradability, liquidity, and other business and policy goals that similar exchanges provide terrestrially ("Imagine a Space Economy without a Commodities Marketplace" to "International Commodities Markets and How They Supplement Statutory Gaps through Efficient Operations" sections), the road map for forming a space commodities exchange might readily proceed by the following steps:

(1) Form a Board of Trade to represent the interests of space economy suppliers, their customers, investors, and other stakeholders in defining what should trade as "space commodities" and the contractual terms more lightweight and practical to do so (see "Space Commodities" section, the Five Buckets of Commodities).
(2) Focus on the space economy as it exists today in LEO and the space commodities readily supplied and used in LEO for servicing terrestrial, lunar, and other needs on a sustainable basis.
(3) Determine the capital needed to support the operations of the space commodities exchange for its first 2 years, including organizational and regulatory costs, marketing, and relating items.
(4) Recruit management experienced in operating commodities and financial institutions, as well as having an interest in growing the space economy.
(5) Raise sufficient capital from the Board of Trade and the public markets to anticipate the needs of the space commodities exchange.
(6) Apply to the CFTC for DCM recognition, on behalf of the Board of Trade.
(7) Develop an "order book" of space commodities that suppliers and their customers will want to put under contract in the first 5 years of operating the exchange, and start filling the Five Buckets with such space commodities' definitions.
(8) Develop the data analytics platform for understanding the space economy by reference to the commodities traded on the exchange.
(9) With the preliminary steps' momentum, consider if an existing commodity or financial exchange might partner with the Board of Trade to add "space commodities" in the Five Buckets to their currently traded range of commodities and financial instruments, and whether such existing exchange rules and processes meet the near and long-term requirements of the Board of Trade for growing the space economy.

Certainly, this road map would change based on input from the Board of Trade, the CFTC, investors, space commodities suppliers, and their customers, and other interested parties.

HOW A SPACE COMMODITIES EXCHANGE PROMOTES THE NATION'S VISION FOR SPACE EXPLORATION

On January 14, 2004, President George W. Bush presented *The Vision for Space Exploration* (2004 VSE), committing the United States to "the fundamental goal of advanc[ing] U.S. scientific, security, and economic interests through a robust space exploration program."[129] Strategies to achieve the Vision included:

- "implement a sustained and affordable human and robotic program to explore the solar system and beyond,"
- "extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations, and"
- "pursue breakthrough technologies, investigate lunar and other space resources, and align ongoing programs to develop sustainable, affordable, and flexible solar system exploration strategies."[129]

The 2004 VSE declared that space exploration is vital to the economic competitiveness of the United States and inspires the education and careers of the nation's youth. In 2006 and 2008, Presidential Science Advisor Dr. John Marburger observed: "As I see it, questions about the Vision [for Space Exploration] boil down to whether we want to incorporate the solar system in our economic sphere, or not."[130,131] The past decade has seen commercial industry step forward to integrate the economic future of the nation with our economic future in space.

Numerous U.S. companies have been established to prospect for and harvest resources on the Moon and asteroids, including Moon Express, Planetary Resources, and Deep Space Industries. These companies have recruited teams of remarkably talented individuals, developed impressive new technologies, and raised tens of millions of dollars of financial capital to reach their goals. Outside of the United States, space exploration has become a rapidly competitive national economic development and national security strategy, supporting teams of young engineers in "start-up companies," "space accelerators," and traditional space industry settings.

But how will resources in space be bought and sold, what form will such transactions take to attract investment in and support of growing the space economy, and how will rights to resources be honored and enforced?

A key element to a vital and growing space economy is ensuring a consistent and growing supply of space commodities in specific orbits, and at predictable times for customers who commit to purchase, lease, or in other ways add value to space resources and products, such as lunar water and other volatiles, regolith from the Moon or asteroids, precious and rare earth materials.

To enable such a space economy, a system must be put in place that will (1) maximize the space economy's growth and systemic safety, (2) provide openness, fairness, and competitiveness, (3) give full commercial expression to the goals of the United Nations Space Treaties, and (4) attract sufficient and persistent investment, financing, and insurance at reasonable rates.

CONCLUSION

The emerging space economy will produce and depend on space commodities that improve the efficiency, safety, and stepwise boldness of exploration, development, and colonization missions. Matching the supply, demand, availability, and quality of space commodities with the science and technology to extract, manufacture, transport, and store them will require innovations in commodity market structures, governance, and operations. Financial investment and insurance market engineering will need to keep pace with the space economy's needs and potential. A Space Commodities Futures Trading Exchange would be an innovative market mechanism that anticipates and enables the accelerating pace of the commercial space industry's evolving road map and dreams.[1]

AUTHOR DISCLOSURE STATEMENT

As a result of researching this article, Bruce Cahan is organizing the Space Commodities Exchange. For the remaining authors, no competing financial interests exist.

REFERENCES

1. ISECG International Space Exploration Coordination Group. The Global Exploration Strategy: The Framework for Coordination. 2007. https://www.nasa.gov/pdf/296751main_GES_framework.pdf. (Last accessed on February 24, 2017).
2. ISECG. The Global Exploration Roadmap. 2011. https://www.nasa.gov/pdf/591067main_GER_2011_small_single.pdf. (Last accessed on February 24, 2017).
3. ISECG. The Global Exploration Roadmap. 2013. https://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf. (Last accessed on February 24, 2017).
4. European Commission. Strategy for Europe. 2016. https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/COM-2016-705-F1-EN-MAIN.PDF. (Last accessed on August 14, 2017).
5. ESA: European Space Agency (ESA). Exploring Together: ESA Space Exploration Strategy. 2015. http://esamultimedia.esa.int/multimedia/publications/ESA_Space_Exploration_Strategy/. (Last accessed on August 14, 2017).
6. NASA. NASA Technology Roadmaps. 2015. https://www.nasa.gov/offices/oct/home/roadmaps/index.html. (Last accessed on February 24, 2017).
7. NAS: National Academies of Sciences, Division on Engineering and Physical Sciences, Aeronautics and Space Engineering Board, Steering Committee for the NASA Technology Roadmap. An Interim Report on NASA's Draft Space Technology Roadmaps. 2011. https://www.nap.edu/download/13228. (Last accessed on February 24, 2017).

8. FAA: Federal Aviation Administration. Commercial Space Transportation: Fiscal Year 2016 Business Plan. 2016. https://www.faa.gov/about/plans_reports/media/2016/AST_Business_Plan.pdf. (Last accessed on February 24, 2017).
9. ESA. Harmonisation of European Space Technology: A Fundamental Role Enhancing European Industry Worldwide Competitiveness. 2016. http://eurospace.org/Data/Sites/1/harmonisationbrochure2016finale.pdf. (Last accessed on August 1, 2017).
10. Griffin MD. The space economy (NASA 50th Anniversary Lecture Series). 2007. www.nasa.gov/pdf/189537main_mg_space_economy_20070917.pdf. (Last accessed on July 29, 2017).
11. OECD: Organization for Economic Cooperation and Development. The Space Economy at a Glance 2014. 2014. http://dx.doi.org/10.1787/9789264217294-en. (Last accessed on September 17, 2017).
12. NASA Office of the Chief Technologist. Emerging Space Report: The Evolving Landscape of 21st Century American Spaceflight. 2014. http://images.spaceref.com/docs/2014/Emerging_Space_Report.pdf. (Last accessed on September 17, 2017).
13. ULA: United Launch Alliance. Transportation Enabling a Robust Cislunar Space Economy. 2016. www.ulalaunch.com/uploads/docs/Published_Papers/Commercial_Space/2016_Cislunar.pdf. (Last accessed on February 24, 2017).
14. Davenport C. Elon Musk provides new details on his 'mind blowing' mission to Mars. 2016. https://www.washingtonpost.com/news/the-switch/wp/2016/06/10/elon-musk-provides-new-details-on-his-mind-blowing-mission-to-mars/. (Last accessed on February 24, 2017).
15. Thomas-Brown M. The Future of Health Care & The Digital Divide: Health and Digital Disparities. https://web.archive.org/web/20170228164243/http://nhitunderserved.org/blogs/blog.html?id=17. (Last accessed on March 20, 2017).
16. ITU: International Telecommunications Union. Measuring the Information Society Report: 2016. 2016. ISBN: 978-92-61-21431-9. www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2016/MISR2016-w4.pdf. (Last accessed on March 20, 2017).
17. Connolly KK, Crosby M. Examining e-Health literacy and the digital divide in an underserved population in Hawaii. Hawaii J Med Public Health. 2014;73(2):44–48.
18. File T, Ryan C. American Community Survey Reports: Computer and Internet Use in the United States: 2013. 2014. https://www.census.gov/content/dam/Census/library/publications/2014/acs/acs-28.pdf. (Last accessed on March 20, 2017).
19. Tedeschi D. The Extraterrestrial Commodities Market—A visionary scientist says that asteroids and comets can be the foundation of a lucrative space-based economy. Air & Space Magazine. 2015. www.airspacemag.com/as-interview/extraterrestrial-commodities-market-180956240/. (Last accessed on March 22, 2017).
20. World Bank. Commodities Market Outlook—October 2017. 2017. http://pubdocs.worldbank.org/en/743431507927822505/CMO-October-2017-Full-Report.pdf. (Last accessed on November 10, 2017).
21. Lee RJ. Law and Regulation of Commercial Mining of Minerals in Outer Space. 2012. ISBN 978-94-007-2038-1. http://link.springer.com/book/10.1007%2F978-94-007-2039-8. DOI 10.1007/978-94-007-2039-8. (Last accessed on March 22, 2017).
22. Meadows D, *et al.* The Limits to Growth. The Club of Rome. 1972. ISBN: 0-87663-165-0. www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf. (Last accessed on August 18, 2017).
23. Wijkman A, Skånberg K. The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy based on Renewable Energy and Resource Efficiency—A Study Pertaining to Finland, France, the Netherlands, Spain and Sweden. The Club of Rome. 2016. https://www.clubofrome.org/wp-content/uploads/2016/03/The-Circular-Economy-and-Benefits-for-Society.pdf. (Last accessed on August 18, 2017).
24. World Economic Forum. Mining & Metals in a Sustainable World 2050—A Case for Action. 2015. www3.weforum.org/docs/WEF_MM_Sustainable_World_2050_report_2015.pdf. (Last accessed on August 18, 2017).
25. Investopedia. Commodity. www.investopedia.com/terms/c/commodity-trader.asp. (Last accessed on August 1, 2017).
26. Churchill Semple C. Geographic factors in the ancient Mediterranean grain trade. Ann Assoc Am Geographers. 1921;11:47–74.
27. Erdkamp P. The Grain Market in the Roman Empire: A Social, Political and Economic Study. 2005. ISBN-13 978-0-521-83878-8. https://doi.org/10.1017/S1047759400005730. (Last accessed on November 10, 2017).
28. Reuters. Antwerp Bourse—World's oldest—Closes. Los Angeles Times. 1997. http://articles.latimes.com/1997/dec/31/business/fi-3623. (Last accessed on February 26, 2017).
29. The Royal Exchange. Heritage. www.theroyalexchange.co.uk/heritage/. (Last accessed on November 10, 2017).
30. Moss D, Kintgen E. The Dojima rice market and the origins of futures trading. Harvard Business School. 2010. Case Study No. 9-709-044. www.hbs.edu/faculty/Pages/item.aspx?num=3684. (Last accessed on November 10, 2017).
31. Taylor C. *History of the Board of Trade of the City of Chicago—Volumes I, II and III*. Chicago: Robert O. Law Company, 1917.
32. CME Group. Timeline of CME Achievements. www.cmegroup.com/company/history/timeline-of-achievements.html. (Last accessed on November 10, 2017).
33. USDA. United States Standards for Grades of Oranges (Texas and States Other Than Florida, California, and Arizona), 7 CFR §§51.680–51.688 (2018).
34. USDA. Grades and Standards. https://www.ams.usda.gov/grades-standards. (Last accessed on June 2, 2017).
35. USDA. Fruit Standards. https://www.ams.usda.gov/grades-standards/fruits. (Last accessed on June 2, 2017).
36. USDA. Agriculture Regulations—Cotton Classing, Testing, and Standards, 7 CFR Part 28 (2018).
37. USDA. Cotton Standards. https://www.ams.usda.gov/grades-standards/cotton. (Last accessed on June 2, 2017).
38. USDA. 2017 Crop Policies and Pilots. https://www.rma.usda.gov/policies/2017policy.html. (Last accessed on November 10, 2017).
39. Henriques DB. New threat to farmers: The market hedge. The New York Times. 2008. www.nytimes.com/2008/04/21/business/21cnd-commodity.html. (Last accessed on June 5, 2017).
40. Tomek WG. Effects of futures and options trading on farm incomes. Cornell Agricultural Economics Staff Paper. 1987. http://publications.dyson.cornell.edu/research/researchpdf/sp/1987/Cornell-Dyson-sp8709.pdf. No. 87-9. (Last accessed on June 5, 2017).
41. Paul AB, Heifner RG, Helmuth JW. Farmers' Use of Forward Contracts and Futures Markets. National Economic Analysis Division, Economic Research Services, Agricultural Economic Report. 1976. https://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT76671306&content=PDF. No. 320. (Last accessed on June 10, 2017).
42. Mark DR, *et al.* Price Risk Management Alternatives for Farmers in the Absence of Forward Contracts with Grain Merchants. Choices, a publication of the Agricultural Economics Association. 2008. www.choicesmagazine.org/UserFiles/file/article_27.pdf. (Last accessed on June 5, 2017).
43. Parcell J, Franken J. Introduction to Hedging Agricultural Commodities with Futures. University of Missouri. 2011. https://extensiondata.missouri.edu/pub/pdf/agguides/agecon/g00602.pdf. (Last accessed on September 25, 2017).
44. Parcell J, Pierce V. Long Hedge Example with Futures. University of Missouri. 2011. https://extensiondata.missouri.edu/pub/pdf/agguides/agecon/g00607.pdf. (Last accessed on September 25, 2017).
45. Parcell J, Franken J. Short Hedge Example with Futures. University of Missouri. 2011. https://extensiondata.missouri.edu/pub/pdf/agguides/agecon/g00608.pdf. (Last accessed on September 25, 2017).
46. University of Missouri. Commodity Marketing. http://extension.missouri.edu/main/DisplayCategory.aspx?C=550. (Last accessed on September 25, 2017).
47. Chicago Mercantile Exchange. An Introduction to Futures and Options. 2006. www.cmegroup.com/files/intro_fut_opt.pdf. (Last accessed on June 2, 2017).
48. Olson DW. 2013 Minerals Yearbook: Diamond, Industrial (Advance Release). USGS: U.S. Geological Survey. 2015. https://minerals.usgs.gov/minerals/pubs/

commodity/diamond/myb1-2013-diamo.pdf. (Last accessed on February 26, 2017).
49. Olson D. Mineral Commodity Summaries. USGS. 2017. https://minerals.usgs.gov/minerals/pubs/commodity/diamond/mcs-2017-diamo.pdf. (Last accessed on February 26, 2017).
50. Vereniging Beurs voor den Diamanthandel. History of the oldest diamond-exchange in the world. 2015. www.diamantbeurs.org/history.html. (Last accessed on February 26, 2017).
51. Antwerp Diamond Bourse. History of the Antwerp Diamond Bourse. https://www.diamondbourseantwerp.com/what-we-do-at-the-antwerp-diamond-bourse/. (Last accessed on February 26, 2017).
52. World Federation of Diamond Bourses. History of the World Federation of Diamond Bourses. 2014. www.wfdb.com/aboutus/history. (Last accessed on February 27, 2017).
53. Vereniging Beurs voor den Diamanthandel. Welcome …125 years of watching over diamonds! 2015. www.diamantbeurs.org/english.html. (Last accessed on February 26, 2017).
54. World Federation of Diamond Bourses. 60 Years of Service. www.wfdb.com/downloads/WFDB_history.pdf. (Last accessed on February 26, 2017).
55. World Diamond Council. History of the World Diamond Council. www.worlddiamondcouncil.com. (Last accessed on February 27, 2017).
56. World Diamond Council. Kimberley Process Scheme: 2016. 2016. https://www.kimberleyprocess.com/en/kpcs-core-document-version-2016-0. (Last accessed on February 27, 2017).
57. Sage HJ. The Industrial Revolution in America. Sage American History. 2013. http://sageamericanhistory.net/gildedage/topics/industrialrevolution.html. (Last accessed on February 27, 2017).
58. ASTM International. ASTM 1898–1998: A Century of Progress. 1999. https://www1.astm.org/IMAGES03/Century_of_Progress.pdf. p. 29. (Last accessed on February 27, 2017).
59. Reagents Inc. Grades/Purity. www.reagents.com/products/grades-purity. (Last accessed on March 15, 2017).
60. Fisher Chemical. Purity Grades for Every Application. 2013. https://fscimage.fishersci.com/cmsassets/downloads/segment/Scientific/pdf/Chemicals/fisherchem_grades.pdf. (Last accessed on March 15, 2017).
61. Haller Jr., JS. The United States Pharmacopoeia: its origin and revision in the 19th century. Bull N Y Acad Med. 1982;58(5):480–492.
62. The United States Pharmacopeial Convention. U.S. Pharmacopeial Convention from 1820 to the present: USP Milestones—A Timeline. www.usp.org/about/history-information-center/usp-milestones-timeline#1820. (Last accessed on March 15, 2017).
63. Till H. Why Some Futures Contracts Succeed and Others Fail: A Survey of Relevant Research. EDHEC Business School. 2014. https://www.edhec.edu/sites/www.edhec-portail.pprod.net/files/publications/pdf/edhec-working-paper-why-some-futures-contracts_1436277798888-pdfjpg. (Last accessed on June 5, 2017).
64. Perez MG. Traders Asked for This Futures Contract, But They Aren't Using It. Bloomberg. 2016. https://www.bloomberg.com/news/articles/2017-04-07/traders-asked-for-this-futures-contract-but-aren-t-using-it. (Last accessed on June 5, 2017).
65. Hathaway K. The potential effects of government intervention in a market economy. Financial Markets International Research Paper. 2007. www.fmi-inc.net/news/pdfs/EffectsGovtIntervention.pdf. (Last accessed on June 5, 2017).
66. Carlton DW. Futures markets: Their purpose, their history, their growth, their successes and failures. J Futures Markets. 1984;4(3):237–271.
67. World Bank Group. Commodity Markets Outlook Quarterly Report. 2017. http://pubdocs.worldbank.org/en/174381493046968144/CMO-April-2017-Full-Report.pdf. (Last accessed on June 7, 2017).
68. Dwyer A, Gardner G, Williams T. Global commodity markets—Price volatility and financialisation. Reserve Bank of Australia Quarterly Bulletin. 2011. https://www.rba.gov.au/publications/bulletin/2011/jun/pdf/bu-0611-7.pdf. (Last accessed on June 7, 2017).
69. Roncoroni A, Fusai G, Cummins M. Handbook of Multi-Commodity Markets and Products: Structuring, Trading and Risk Management. West Sussex, United Kingdom: John Wiley & Sons Ltd. Publishers, 2015. ISBN: 978-0-470-74524-3. www.wiley.com/WileyCDA/WileyTitle/productCd-047074524X.html. (Last accessed on June 5, 2017).
70. United Nations. Standard International Trade Classification—Revision 4. United Nations Department of Economic and Social Affairs–Statistics Division. 2006. ISBN 92-1-161493-7. https://unstats.un.org/unsd/publication/SeriesM/SeriesM_34rev4E.pdf. (Last accessed on August 1, 2017).
71. Marian R, Wårell L. A Handbook of Primary Commodities in the Global Economy, 2nd edition. Cambridge University Press. 2017. ISBN: 9781107129801. www.cambridge.org/us/academic/subjects/economics/natural-resource-and-environmental-economics/handbook-primary-commodities-global-economy-2nd-edition?format=HB&isbn=9781107129801. (Last accessed on August 1, 2017).
72. Kenney S. The Foundations of Government Contracting—Contracting professionals would do well to understand not only their position in the structure, but their place in the cycle as well, and how that cycle came to be. J Contract Manage. 2007. www.ago.noaa.gov/acquisition/docs/foundations_of_contracting_with_the_federal_government.pdf. (Last accessed on February 27, 2017).
73. GAO: U.S. United States Government Accountability Office. Federal Procurement—Smarter Buying Initiatives Can Achieve Additional Savings, but Improved Oversight and Accountability Needed. GAO. 2016. www.gao.gov/assets/690/680634.pdf. (Last accessed on February 28, 2017).
74. GAO. Federal Acquisition Challenges and Opportunities in the 21st Century. Comptroller General's Forum. 2006. www.gao.gov/assets/210/202977.pdf. (Last accessed on November 10, 2017).
75. Partnership for Public Service. Innovation is a Contact Sport: Ways that agencies can achieve innovative outcomes through acquisitions. Government Executive Magazine. 2016. https://www.govexec.com/media/gbc/docs/pdfs_edit/020916cc1.pdf. (Last accessed on November 10, 2017).
76. Jakhu RS, Pelton JN. Global Space Governance: An International Study. Cham, Switzerland: Springer International Publishing AG. 2017.
77. Cahan BB. Financing the NSDI: National Spatial Data Infrastructure—Aligning Federal and Non-Federal Investments in Spatial Data, Decision Support and Information Resources. FGDC: Federal Geographic Data Committee. 2000. https://www.fgdc.gov/resources/whitepapers-reports/sponsored-reports/urbanlogic_exsum.pdf. (Last accessed on March 15, 2017).
78. Cahan BB. The Value Proposition for Geospatial One-Stop. FGDC. 2004. https://www.fgdc.gov/policyandplanning/future-directions/action-plans/valuepropositionofgeospatialonestop100604final.pdf. (Last accessed on March 15, 2017).
79. Chui M, Farrell D, Jackson, K. How Government Can Promote Open Data and Help Unleash over $3 Trillion in Economic Value—Open data has the potential to unleash innovation and transform every sector of the economy. Government can play a critical role in ensuring that stakeholders capture the full value of this information. McKinsey & Company. 2014. www.mckinsey.com/industries/public-sector/our-insights/how-government-can-promote-open-data. (Last accessed on March 13, 2017).
80. ICSU: International Council for Science, IAP: Inter-Academy Partnership, ISSC: International Social Science Council and TWAS: The World Academy of Sciences. Open data in a big data world—An international accord (extended version). Sci Int. 2015. www.icsu.org/science-international/accord/open-data-in-a-big-data-world-long. (Last accessed on March 15, 2017).
81. Landry BD. A tragedy of the anticommons: The economic inefficiencies of space law. Brooklyn J Int Law. 2013;38(2):523–578.
82. Horn N. Commercial mining of celestial bodies: A legal roadmap. Georgetown Int Environ Law Rev. 2015;27. https://gielr.files.wordpress.com/2015/12/harn.pdf. (Last accessed on April 17, 2017).
83. Daniels V, *et al.* The pathway to a safe and effective medication formulary for exploration spaceflight. NASA Report JSC-CN-37907. NASA. 2017. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160013658.pdf. (Last accessed on March 17, 2017).
84. HM Treasury. Global commodities: A long-term vision for stable, secure and sustainable global markets. 2008. http://webarchive.nationalarchives.gov.uk/

20130129110402/http://www.hm-treasury.gov.uk/d/globalcommodities.pdf. (Last accessed on April 18, 2017).
85. Malik Y, Niemeyer A, Ruwadi B. Building the supply chain of the future. McKinsey Q. 2011. www.mckinsey.com/business-functions/operations/our-insights/building-the-supply-chain-of-the-future. (Last accessed on August 15, 2017).
86. NIST: National Institute of Standards and Technology. Boeing and Exostar: Cyber security supply chain risk management. NIST U.S. Resilience Project. https://www.nist.gov/sites/default/files/documents/itl/csd/NIST_USRP-Boeing-Exostar-Case-Study.pdf. (Last accessed on August 13, 2017).
87. Vulkan N. The Economics of E-Commerce: A Strategic Guide to Understanding and Designing the Online Marketplace. Princeton University Press. 2003. ISBN: 9780691089065. https://books.google.com/books?id=w7sYCQ_SzekC. (Last accessed on April 25, 2017).
88. Fanelli V. Commodity-linked arbitrage strategies and portfolio management (Handbook of Multi-Commodity Markets and Products: Structuring, Trading and Risk Management). 2015. ISBN: 978-0-470-74524-3. www.wiley.com/WileyCDA/WileyTitle/productCd-047074524X.html. Section 20.1.1.
89. H.M. Treasury, Bank of England, & Financial Conduct Authority. Fair and Effective Markets Review—Final Report. 2015. https://www.bankofengland.co.uk/-/media/boe/files/report/2015/fair-and-effective-markets-review-final-report.pdf. (Last accessed on April 14, 2017).
90. Isherwood G. Algorithmic trading in commodity markets. Commodities Magazine. 2010. www.thecmlink.com/wordpress/wp-content/uploads/2013/10/2010-September-Algorithmic-Trading-in-Commodity-Mark.pdf. (Last accessed on April 17, 2017).
91. CFTC. Futures Markets Basics. www.cftc.gov/consumerprotection/educationcenter/futuresmarketbasics/index.htm. (Last accessed on April 17, 2017).
92. CME Group. CME Rulebook—Chapter iii. Definitions. Chicago Mercantile Exchange. www.cmegroup.com/rulebook/files/CME_Definitions.pdf. (Last accessed on June 12, 2017).
93. Hull JC. Options, futures and other derivatives. Pearson Education—Prentice Hall. 2012. ISBN 978-0-13-216494-8. http://workofark.com/pdf/options.PDF. (Last accessed on June 12, 2017).
94. Lyuu Y-D. Chapter 12—Forwards, futures, futures options and swaps (Financial Engineering and Computation: Principles, Mathematics, Algorithms). Cambridge University Press. 2002. ISBN: 9780521781718. www.cambridge.org/gb/academic/subjects/mathematics/mathematical-finance/financial-engineering-and-computation-principles-mathematics-algorithms?format=HB&isbn=9780521781718. (Last accessed on August 15, 2017).
95. Declerk F. Agricultural and soft markets—Chapter 9 (Handbook of Multi-Commodity Markets and Products: Structuring, Trading and Risk Management). 2015. ISBN: 978-0-470-74524-3. www.wiley.com/WileyCDA/WileyTitle/productCd-047074524X.html. (Last accessed on August 15, 2017).
96. U.S. Congress. Commodities Exchange Act—Section 1a(9). 7 USC Section 1a (9).http://uscode.house.gov/browse/prelim@title7/chapter1&edition=prelim. (Last accessed on April 18, 2017).
97. U.S. Congress. Surface Mining Control and Reclamation—30 USC Chapter 25. http://uscode.house.gov/view.xhtml?path=/prelim@title30/chapter25&edition=prelim. (Last accessed on November 10, 2017).
98. U.S. Department of Interior. Regulating Coal Mines. Office of Surface Mining Reclamation and Enforcement. https://www.osmre.gov/programs/rcm.shtm. (Last accessed on April 18, 2017).
99. U.S. Congress. Jurisdiction of the Commodity Futures Trading Commission, 7 USC Section 2(a). https://www.gpo.gov/fdsys/pkg/USCODE-2015-title7/html/USCODE-2015-title7-chap1.htm. (Last accessed on April 18, 2017).
100. U.S. Congress. Definition of Excluded Commodity, 7 USC Section 1a (19). https://www.gpo.gov/fdsys/pkg/USCODE-2015-title7/html/USCODE-2015-title7-chap1.htm. (Last accessed on April 18, 2017).
101. CFTC. Title 17—Commodity and Securities Exchanges—Part 38 Designated Contract Markets. 17 CFR Part 38. https://www.gpo.gov/fdsys/pkg/CFR-2016-title17-vol1/xml/CFR-2016-title17-vol1-part38.xml. (Last accessed on March 9, 2017).
102. CFTC. Grandfather Relief to Exempt Commercial Markets and Exempt Boards of Trade. 2010. www.cftc.gov/PressRoom/PressReleases/pr5891-10. (Last accessed on June 6, 2017).
103. CFTC. Notice of Proposed Rulemaking relating to Core Principles and Other Requirements for Designated Contract Markets. Federal Register. 2010; 75(245). www.cftc.gov/idc/groups/public/@lrfederalregister/documents/file/2010-31458a.pdf. (Last accessed on June 6, 2017).
104. CFTC. Trading Organizations—Designated Contract Markets (DCM). 2017. https://sirt.cftc.gov/SIRT/SIRT.aspx?Topic=TradingOrganizations&implicit=true&type=DCM&CustomColumnDisplay=TTTTTTTT. (Last accessed on March 9, 2017).
105. Shadab H. Regulating bitcoin and block chain derivatives. New York Law School Legal Studies Research Paper. 2014. www.cftc.gov/idc/groups/public/@aboutcftc/documents/file/gmac_100914_bitcoin.pdf. (Last accessed on June 9, 2017).
106. Green RA. If you want to trade bitcoins, first learn CFTC rules. Forbes Magazine. 2017. https://www.forbes.com/sites/greatspeculations/2017/02/21/if-you-want-to-trade-bitcoins-first-learn-cftc-rules/. (Last accessed on June 9, 2017).
107. CFTC. CFTC Orders Bitcoin Options Trading Platform Operator and its CEO to Cease Illegally Offering Bitcoin Options and to Cease Operating a Facility for Trading or Processing of Swaps without Registering—In First Action against an Unregistered Bitcoin Options Trading Platform, CFTC Holds that Bitcoin and Other Virtual Currencies Are a Commodity Covered by the Commodity Exchange Act. CFTC Press Release 7231-15. 2015. www.cftc.gov/PressRoom/PressReleases/pr7231-15. (Last accessed on June 9, 2017).
108. CFTC. CFTC Orders Bitcoin Exchange Bitfinex to Pay $75,000 for Offering Illegal Off-Exchange Financed Retail Commodity Transactions and Failing to Register as a Futures Commission Merchant. CFTC Press Release PR 7380-16. 2016. www.cftc.gov/PressRoom/PressReleases/pr7380-16. (Last accessed on June 9, 2017).
109. CFTC. Trading Organizations—Designated Contract Markets (DCM). https://sirt.cftc.gov/SIRT/SIRT.aspx?Topic=TradingOrganizations&implicit=true&type=DCM&CustomColumnDisplay=TTTTTTTT. (Last accessed on December 15, 2017).
110. CFTC. Designated Contract Markets (DCMs). www.cftc.gov/IndustryOversight/TradingOrganizations/DCMs/index.htm. (Last accessed on March 15, 2017).
111. CFTC. Form DCM: Contract Market Application or Amendment to Application for Designation. GPO. Appendix A to 17 CFR Part 38. https://www.gpo.gov/fdsys/pkg/CFR-2016-title17-vol1/pdf/CFR-2016-title17-vol1-part38-appA.pdf. (Last accessed on March 9, 2017).
112. U.S. Congress. Commodity Exchange Act—Section 5b 7 USC § 7a-1. www.cftc.gov/files/ogc/comex060601.pdf. (Last accessed on August 15, 2017).
113. CFTC. Derivatives Clearing Organizations—17 CFR Part 39. https://www.gpo.gov/fdsys/pkg/CFR-2016-title17-vol1/xml/CFR-2016-title17-vol1-part39.xml. (Last accessed on April 19, 2017).
114. CFTC. Derivatives Clearing Organizations. www.cftc.gov/IndustryOversight/ClearingOrganizations/index.htm. (Last accessed on March 15, 2017).
115. CFTC. Form DCO—Derivatives Clearing Organization—Application for Registration. www.cftc.gov/idc/groups/public/@clearingintermediary/documents/file/formdco-pdf.pdf. (Last accessed on March 15, 2017).
116. CFTC. Supervisory Stress Test of Clearinghouses. 2016. www.cftc.gov/idc/groups/public/@newsroom/documents/file/cftcstresstest111516.pdf. (Last accessed on April 17, 2017).
117. Wikipedia. List of commodities exchanges (sorted by country and commodity traded). https://en.wikipedia.org/wiki/List_of_commodities_exchanges. (Last accessed on April 17, 2017).
118. Jiang M. Asia-Pacific Commodity Exchange Consolidation Imminent? A Study of Asian-Pacific Commodity Exchanges and Their Possible Consolidation in the Near Future. 2011. http://mmss.wcas.northwestern.edu/thesis/articles/get/759/Jiang2011.pdf. (Last accessed on April 19, 2017).
119. Jaswal A. Commodity exchanges: Consolidation drivers and implications. Celent. 2009. http://celent.com/reports/commodity-exchanges-consolidation-drivers-and-implications. (Last accessed on April 19, 2017).
120. Blas J. Grain traders eye further consolidation. Financial Times. 2012. https://www.ft.com/content/7ff323ae-726f-11e1-9c23-00144feab49a. (Last accessed on April 19, 2017).

121. Hecht A. Exchange Consolidation—The business model for futures exchanges has come a long way… 2016. https://www.thebalance.com/exchange-consolidation-808852. (Last accessed on April 19, 2017).
122. Bhayani R. Consolidation in commodity market space: ICEX-NMCE considering merger—ICEX getting offers from Indian sight holders of De Beers to buy stake. Business Standard. 2017. www.business-standard.com/article/markets/consolidation-in-commodity-market-space-icex-nmce-considering-merger-117022000235_1.html. (Last accessed on April 19, 2017).
123. Surden H. Computable contracts. University of California at Davis Law Review. 2012;46. http://lawreview.law.ucdavis.edu/issues/46/2/articles/46-2_surden.pdf. (Last accessed on April 17, 2017).
124. Marvin R. Blockchain in 2017: The year of smart contracts. PC Magazine. 2016. www.pcmag.com/article/350088/blockchain-in-2017-the-year-of-smart-contracts. (Last accessed on April 19, 2017).
125. Caytas JD. Developing blockchain real-time clearing and settlement in the EU, U.S., and globally. Columbia J Eur Law. 2016. http://cjel.law.columbia.edu/preliminary-reference/2016/developing-blockchain-real-time-clearing-and-settlement-in-the-eu-u-s-and-globally-2. (Last accessed on April 19, 2017).
126. Deloitte. Blockchain Applications in Energy Trading. 2016. www.the-blockchain.com/docs/Blockchain-Applications-in-Energy-Trading-Deloitte-uk.pdf. (Last accessed on April 19, 2017).
127. Stafford P. FT Explainer: The blockchain and financial markets. Financial Times. 2015. https://www.ft.com/content/454be1c8-2577-11e5-9c4e-a775d2b173ca. (Last accessed on April 19, 2017).
128. Tapscott D, Tapscott A. Blockchain Revolution: How the Technology Behind Bitcoin is Changing Money, Business, and The World. New York, NY: Penguin Random House LLC. 2016. https://www.penguinrandomhouse.com/books/531126/blockchain-revolution-by-don-tapscott-and-alex-tapscott/9781101980132/.
129. NASA. The vision for space exploration. NASA. 2004. https://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf. (Last accessed on November 10, 2017).
130. Marburger J. 44th Robert H. Goddard Memorial Symposium March 15, 2006 Keynote Address. National Space Society. 2006. www.nss.org/resources/library/spacepolicy/marburger1.pdf. (Last accessed on November 10, 2017).
131. Marburger J. 46th Robert H. Goddard Memorial Symposium. NASA. 2008. https://www.nasa.gov/pdf/376588main_03%20-%2003-06-08%20jhm%20Goddard%20Symposium.pdf. (Last accessed on November 10, 2017).

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Appendix

APPENDIX 1. INDUSTRIAL AGE CONSENSUS TO COMMODITY STANDARDS THROUGH THE ASTM

The ASTM is an early Industrial Age example of moving competitors to embrace standards for fabrication of metals and other products, and provides a vivid historical analogy for commodity standards needed for commercialization of Space Age.[58(pp. 29–33)]

RESISTANCE TO STANDARDS

Progress (on standards for railroad materials and construction) was nevertheless slow. Suppliers in many industries such as construction and metallurgy objected to standard material specifications and testing procedures because they feared that strict quality controls would make customers more inclined to reject items and default on contracts. Even in iron and steel, where quality definitions and standards made greater headway than in other industries, material specifications remained controversial. The ones that existed were highly customized and applied only to a specific order. Industrywide standard specifications were unheard of, making life difficult for large buyers. Without standard specifications, and with each mill following its own material testing procedures, buyers of industrial products were unable to ensure uniformity and frequently found reason to complain about the uneven quality of steel rails for railroads.

The Pennsylvania Railroad, the largest corporation of the 19th century, played a key role in the quest for standard specifications. Its efforts in this field were initiated by Charles Dudley, who received his PhD from Yale University in 1874, and who later became the driving force behind ASTM. Dudley organized the railroad's new chemistry department, where he investigated the technical properties of oil, paint, steel, and other materials the Pennsylvania Railroad bought in large quantities. Based on his research, Dudley issued standard material specifications for the company's suppliers.

Dudley soon realized that he had taken on a formidable task. In 1878, he published his first major report, "The Chemical Composition and Physical Properties of Steel Rails," in which he analyzed the durability of different types of steel rails. It concluded that mild steel produced a longer lasting rail than hard steel, and Dudley recommended an improved formula for mild steel for rails to be used by Pennsylvania. His report raised a firestorm among steel masters, who disputed its findings. The application of Dudley's new formula, they charged, produced unnecessary expenses that increased production costs. Steel producers, determined to keep full control over output and quality control, viewed standard specifications issued by their customers as unacceptable meddling. Dudley later reported that steel companies often told the railroads that "if they did not take the rails offered (by the manufacturers), they would not get any."

The disappointing response to his first report reinforced Dudley's resolve to initiate a constructive dialogue between suppliers and their customers. Each party had much to learn from the other. Steel makers knew more about practical production issues and the industry's cost structure than their customers, while railroads, locomotive builders, and other users of steel products had better knowledge of a material's long-term performance, knowledge that could help manufacturers improve the quality of rails, plates, and beams. Dudley concluded that "a good specification needs both the knowledge of the product's behavior during manufacture and knowledge of those who know its behavior while in service."

The introduction of more powerful locomotives, heavier rolling stock, and longer trains gave buyers an additional incentive to work more closely with their suppliers. Statistics compiled by railroad engineers indicated that the average wheel load of cars increased 75%, and traffic volume rose more than 300% during the late 19th century. Rail manufacturers needed this kind of data to supply steel that conformed to higher performance standards. However, the lack of cooperation between producers and users of steel rails was an enormous detriment to such improvements.

THE BIRTH OF CONSENSUS

Dudley's efforts to find a solution to these seemingly intractable problems facilitated the formation of ASTM, which was committed to building a consensus on standards for industrial materials. The founding of the organization in 1898 was preceded by several key initiatives that laid the groundwork.

Dudley, whose experiences during the 1880s gave him a better picture of the antagonistic attitudes that marred relationships between the Pennsylvania Railroad and its suppliers, proposed an innovative system of technical committees. These committees provided representatives of the main parties with a forum to discuss every aspect of specifications and testing procedures for a given material. The goal was to reach a consensus that was acceptable to both producers and to the customer, that is, the railroad. Although many initial meetings ended in failure due to the inflexibility of the parties involved, Dudley's system held considerable promise and later formed the basis for ASTM's committee structure.

Dudley's call for consensus building, which he articulated in meetings of the American Chemical Society and the International Railway Congress, fell on fertile ground in the engineering community.

His ideas contributed to the formation of the International Association for Testing Materials (IATM), which organized working committees to discuss testing methods for iron, steel, and other materials.

In its bylaws, the organization dedicated itself to "the development and unification of standard methods of testing; the examination of technically important properties of materials of construction and other materials of practical value, and also to the perfection of apparatus used for this purpose."

The International Association encouraged members to form national chapters. On June 16, 1898, seventy IATM members met in Philadelphia to form the American Section of the International Association for Testing Materials. The members grappled with two questions that were widely discussed throughout the engineering community at the turn of the century. First, how could standards for materials contribute to industrial progress, and second, how could producers and users of industrial materials reach a consensus on standards? ASTM's early history was, in large part, a quest to find answers to these pivotal questions.