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ABSTRACT
Recent propulsion system trade studies conducted have concluded that traditional chemical propulsion systems, when scaled down to CubeSat sizes, deliver vanishingly small amounts of impulse per unit volume, even when the smallest available COTS components are assumed. This effectively has created a barrier that seemingly can only be broken with the employment of cold gas systems, due to their reduction and simplification of propulsion system components and the relative ease of the system design itself. Further disadvantages of chemical propulsion systems have included toxicity-related handling restrictions, barring most mission planners from considering these types of systems for secondary payload propulsion trade studies. Use of low-toxicity alternatives has been hindered by a disparity between the typically very limited power budget of nanosatellites and the associated high preheat temperatures required with current state-of-the-art green ionic liquid monopropellant thrusters. Aerojet has developed a comprehensive solution by determining that additive manufacturing processes, combined with miniaturization of propulsion system components, can be employed to break through this barrier by multi-purposing the system structure to replace traditional add-on components, maximizing the use of dry volume, and minimizing the number of overall components and required assembly steps. This results in a propulsion system that can be packaged into a 1U volume that can bolt onto, or be integrated within, a standard CubeSat chassis, for costs low enough to support the simplest of missions. This system can be tailored for multiple levels of ΔV capability, depending on the mission planner’s requirements, by employing a variety of propellants ranging from cold-gas condensable, hydrazine monopropellant, or AF-M315E green advanced monopropellant. This results in ample ΔV capability to enable CubeSat missions like orbital debris management, constellation deployment, scattering and coalescence, or simple drag-make up to support newly-emerging low altitude imaging applications. This system has been designed from the start with input from range safety personnel to ensure compliance to AFSCM91-710.

INTRODUCTION
The CubeSat platform has greatly reduced the barrier to entry for space missions, resulting in significant market growth. Many low cost launch opportunities are available for CubeSats and as a result the number of CubeSats launched is increasing significantly each year. Due to a lack of high-impulse propulsive capabilities, CubeSat missions are effectively confined to their dispersal orbits. Without propulsion the CubeSat platform cannot realize its total addressable market, which will limit the exponential growth that CubeSats have enjoyed in recent years. Propulsive capabilities enable the CubeSat platform to access the wider range of missions that will strengthen the value proposition of the platform and ensure continued explosive growth in the market. Propulsive capabilities ranging from ~10m/s for small dispersal maneuvers to >200m/s for large apogee maneuvers are required. To further compound the problem, recent propulsion system trade studies conducted have concluded that traditional chemical propulsion systems, when scaled down to CubeSat sizes, deliver vanishingly small amounts of total impulse per unit volume, even when the smallest available COTS components are assumed.

Aerojet has developed a comprehensive solution by demonstrating that additive manufacturing processes, together with highly miniaturized system components, can be employed to create a product line of high-impulse CubeSat Modular Propulsion Systems (MPS) that package within CubeSat volumes and satisfy the propulsive needs of the CubeSat community. The product line simplifies propulsion mission planning and integration along with enabling more rideshare flexibility so that any level of CubeSat builder can consider a propulsive mission.

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PRODUCT LINE OVERVIEW

In 2011, Aerojet began development of a 1U modular propulsion system called the CubeSat High-impulse Adaptable Modular Propulsion System (CHAMPS) designated “MRS-142” to address the emerging need for CubeSat propulsion systems. Leveraging designs and components developed for the MRS-142 along with key new technologies enabled Aerojet to develop the CubeSat Modular Propulsion Systems product line shown in Table 1. The systems leverage common parts and designs in order to reduce non-recurring engineering and to achieve economies of scale that will enable reduced cost and lead times as product line production rates increase. The objective of the CubeSat MPS product line is to simplify mission planning, system selection, and satellite integration to the point that any level of CubeSat builder can consider a propulsive mission. This objective is accomplished through the following features:

- Catalog of standard systems with clear propulsive capabilities listed
- “U” based form factor that enables simple mechanical interfacing
- Elimination of requirement for fluidic connections typically required of the tightly integrated propulsion systems found on larger satellites
- Propulsion system control unit with a single power and data connection that simplifies electrical and software integration

Table 1: CubeSat Modular Propulsion Systems Product Line

<table>
<thead>
<tr>
<th>Product Image</th>
<th>Product Number</th>
<th>Description</th>
<th>ΔV for 3U 4kg BOL</th>
<th>ΔV for 6U 10kg BOL</th>
</tr>
</thead>
</table>
|               | MPS-110       | • System Mass: Varies depending on selected size  
|               |               | • Propellant: Inert gas  
|               |               | • Propulsion: 1 to 4 cold gas thrusters | 10 m/s | N/A |
|               | MPS-120       | • System Mass: <1.3kg dry, <1.6kg wet  
|               |               | • Propellant: Hydrazine  
|               |               | • Propulsion: Four 0.26—2.8 N (BOL) rocket engines | 209 m/s | 81 m/s |
|               | MPS-130       | • System Mass: <1.3kg dry, <1.6kg wet  
|               |               | • Propellant: AF-M315E  
|               |               | • Propulsion: Four TBD—1 N (BOL) rocket engines | 340 m/s | 130 m/s |
|               | MPS-120XW     | • System Mass: <2.4kg dry, <3.2kg wet  
|               |               | • Propellant: Hydrazine  
|               |               | • Propulsion: Four 0.26—2.8 N (BOL) rocket engines | 440 m/s | 166 m/s |
|               | MPS-120XL     | • System Mass: <2.4kg dry, <3.2kg wet  
|               |               | • Propellant: Hydrazine  
|               |               | • Propulsion: Four 0.26—2.8 N (BOL) rocket engines | 539 m/s | 200 m/s |
| Image Coming Soon | MPS-160     | • System Mass: TBD  
|               |               | • Propellant: Xenon  
|               |               | • Propulsion: 80W Solar Electric Power/Solar Electric Propulsion System (SEP²) | N/A | >2,000 m/s |

ENABLING TECHNOLOGICAL INNOVATIONS

Miniaturized Rocket Engine Technology

Aerojet investments to commercialize technologies stemming from small form factor missile defense applications has enabled miniature rocket engines and valves capable of supporting CubeSat missions. The resulting MR-14X series of engines realizes a ~4X reduction in volume as shown in Figure 1. Aerojet’s efforts to adapt miniature rocket engine technology for AF-M315E propellant enable both hydrazine and AF-M315E solutions.

Figure 1: Aerojet Miniature Rocket Engine Compared with a Standard Rocket Engine
Additive Manufacturing Process Infusion

Subtractive manufacturing is a generic term used to describe a manufacturing process that removes material from a piece of stock in order to fabricate a part. Examples of subtractive manufacturing processes include: milling, turning, cutting, and drilling. In contrast, Additive manufacturing is a generic term used to describe a manufacturing process that deposits and bonds material together to fabricate a part. Additive manufacturing processes produce parts directly from a digital design. Additive manufactured parts typically require little or no tooling, significantly reducing the cost and lead time of designing, manufacturing, and maintaining tools. If fixtures or tooling are needed they can typically be fabricated during the build process, minimizing the need to create tools ahead of the build or maintain them after the build. The reduced requirement for tooling significantly reduces setup time and cost as well as inventory costs. Additive manufacturing processes typically consume only the material needed to make the part. Typically, most residual material used during the process is re-usable for fabrication of future batches of parts. Additive manufacturing eliminates the need for cutting fluids that are required in subtractive manufacturing processes. The combination of efficient use of material and elimination of support fluids results in significant reductions in material cost and waste. Overall, additive manufacturing process benefits can realize significant reductions in fabrication time and cost. These benefits enable opportunities for more design iterations than traditionally possible, enabling lower cost development programs with higher quality design outputs that are typically ready for direct transition to low volume production. These characteristics are of high importance to the typically long duration, high cost development programs and ultimately low volume production of spacecraft systems.

Current additive manufacturing machines are constrained to build envelopes of ~30 cm³. The MPS-100 product line includes propulsion systems that fit the standard 1U CubeSat envelope of ~10 cm x 10 cm x 10 cm, making these systems ideal candidates for demonstration and infusion of additive manufacturing process technology. Aerojet has embraced the use of additive manufacturing methods and has begun infusion of new design philosophies and manufacturing processes to develop more affordable propulsion systems. The MPS-120 and MPS-130 liquid propulsion systems utilize a piston tank that includes a piston, propellant tank, and pressurant tank. Some components include internal flow passages that were identified as opportunities for improvements with additive manufacturing. Figure 2 shows how design for additive manufacturing enables improvements that reduce component count and eliminate potential leak paths in the system. Figure 3 demonstrates how additive manufacturing removes costly weld/inspection processes. These are just some examples of the benefits offered by additive manufacturing for propulsion systems. Aerojet is working to demonstrate that many types of additive manufacturing processes can be applied to the MPS-100 product line including: Electroforming (EL-Form®), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Laser Engineered Net Shaping (LENS™).

![Additive Manufacturing Process Infusion](image_url)
enables refractory metals to be formed into dense, non-porous and crack-free layers. The EL-Form® process can create component structures on mandrels and/or dense coatings applied existing parts. The EL-Form® process was used to produce the Ir/Re chamber and nozzle for MR-143 engines in the MPS-130 system shown in Figure 4. An operational hotfire demonstration of these components is planned for 2013.

**Figure 4: EL-Form® Components**

The SLM and EBM processes deposit powder in layered fashion and apply laser (SLM) or electron beam (EBM) to sinter powder. Figure 5 are examples of Inconel and titanium components produced by SLM. Figure 6 presents as-printed propellant tank components manufactured by EBM. Operational demonstrations with these components is planned for 2013.

**Figure 5: SLM Additive Manufactured Components**

Laser Engineered Net Shaping (LENS™) is a new manufacturing technology that simultaneously sprays and sinters powder, reducing or eliminating the need for powder removal required by SLM and EBM. Work is ongoing to demonstrate a LENS™ version of the common piston tank. An operational demonstration of the LENS™ tank is planned for 2013.

Demonstration of additive manufacturing production capabilities enables product line development, production, scaling, and tailoring at substantially lower cost and schedules than subtractive manufacturing processes alone. While the objective of the product line is to offer standardized parts, it is recognized that some customers will require non-standard sizes and geometries to fit within available space or to maximize use of available space. The use of additive manufacturing in the standard products enables Aerojet to offer non-standard configurations that do not necessarily require full re-qualification of the system. As an example, 1U and 2U variants of the MPS-120 will be standard, however it is possible to quickly develop and produce a 1.5U version if required by a customer.

**Figure 6: As-Printed EBM Additive Manufactured Piston Tank Components**

**Solar Electric Power/Solar Electric Propulsion (SEP²) System Architecture**

Several companies have offered electric propulsion systems for CubeSats capable of low ΔV and attitude control; however these systems have realized little mission utility. In order to truly benefit from electric propulsion, an apogee solar electric propulsion (SEP) system is desired that can provide significantly more ΔV than chemical systems. However, the cost and mass of electronics in typical apogee electric propulsion solutions are prohibitive on such a small scale. In order for an electric propulsion system to be effective on a platform as small and low cost as a CubeSat, a different approach is required compared with larger satellites.
For several years, Aerojet has been working on a technology called Direct Drive which operates electric thrusters directly from high voltage solar arrays in an attempt to boost efficiency, reduce components, and reduce waste heat. Previous Direct Drive development activities have focused on multi-kilowatt systems. However, the same technology applied to the CubeSat platform significantly reduces the mass and cost of power electronics to the point that primary electric propulsion on CubeSats becomes feasible. An integrated solar power system and direct drive solar electric propulsion control unit enabled Solar Electric Power and Solar Electric Propulsion (SEP²) system enables electric propulsion apogee systems for CubeSats. Figure 7 is an example comparison of a traditional solar electric propulsion system with Aerojet’s SEP² system concept.

**Figure 7: Comparison of Traditional and SEP² Systems**

**MODULAR PROPULSION SYSTEM PRODUCT DESCRIPTIONS**

**MPS-120 Hydrazine Monopropellant Propulsion System**

The MPS-120 maintains much of the original MRS-142 design with some significant changes to align with the overall product line approach. The system has been simplified with the new fluidic schematic shown in Figure 8. An additive manufactured titanium piston tank replaces the previous machined aluminum tank design of the MRS-142. While the aluminum tank is still an optional variant of the new MPS-120 product, the new baseline titanium version provides comparable ΔV and enables more commonality within the product line, reducing system costs. MPS-120 designs are complete and fabrication is currently under-way with MR-142 engines and additive manufactured titanium piston tank nearing completion and readiness for integrated testing.

**Figure 8: MPS-120 System Schematic**

**MPS-130 AF-M315E Monopropellant Propulsion System**

The MPS-130 is a new product offering derived from the MPS-120. Figure 9 presents the fluid schematic for the MPS-130 which is almost identical to the MPS-120 except that a burst disk is not required for the AF-M315E green monopropellant and the system employs new MR-143 engines capable of operating on AF-M315E green monopropellant. The MR-143 engines are of similar size to the MR-142, but utilize rhenium chambers that survive the higher combustion temperatures of AF-M315E propellant. At the time of this writing, the MPS-130 design and drawings are complete, and fabrication is currently under-way with MR-143 engine components produced and ready for engine assembly.

**Figure 9: MPS-130 System Schematic**
**MPS-110 Cold Gas System**

The MPS-110 Cold Gas system is being developed to provide a propulsive capability for missions on small platforms that need minimal ΔV to achieve their mission objectives. Applications would primarily be initial dispersion, minor orbit adjustments, or attitude control. The MPS-110 system derives valves, filter, and tank design from the MPS-120 system mentioned previously. Figure 10 is the fluidic schematic of the MPS-110. The system is capable of operating with a variety of pressurants such as GN2 or condensables enabling significant mission tailoring. MPS-110 pressurants have been selected and operational behaviors are well understood.

![Figure 10: MPS-110 System Schematic](image)

**MPS-160 Electric Propulsion System**

The MPS-160 is a concept system that differs significantly from the systems presented thus far in that it is a 2U system that includes both power and propulsion using the aforementioned SEP² system architecture. The MPS-160 concept development is aimed at developing such a system that would ultimately be capable of providing >2,000m/s to a 6U CubeSat from a 2U propulsion and power package. Figure 11 presents the MPS-160 system schematic. A Hall thruster is used to represent the apogee propulsion; however multiple types of electric thrusters are applicable. Hall thrusters, gridded ion thrusters, and other types of thrusters are in development at the power, voltage, and specific impulse levels required by the MPS-160 system enabling the system to support a wide range of missions.

![Figure 11: MPS-160 System Schematic](image)

**MISSION APPLICATIONS**

**Missions Requiring Dispersal**

Every satellite begins its mission life with a deployment event from the launch vehicle upper stage, and to prevent re-contact after a number of orbits if the upper stage is not actively de-orbited, propulsive maneuvers are typically employed by the satellite to assure that collision does not occur with the upper stage. Alternatively, some satellite missions may desire to conduct propulsive maneuvers to “scatter” away from the larger upper stage, which can easily be tracked by amateur radio operators and launch trackers. Secondary payloads to date typically reserve any minimal ΔV capability found with cold gas systems for utmost critical mission events like attitude control or end-of-life de-orbit requirements. High-impulse propulsion systems, such as the MPS-120 CHAMPS, can provide secondary payloads with the tactical advantages that larger satellites have enjoyed for decades. Figure 12 shows the dispersal capabilities of Aerojet’s CubeSat Modular Propulsion Systems product line to impart 5 m/sec of ΔV to the maximum satellite mass that is achievable. This amount of ΔV is considered the minimum needed to achieve safe and tactical deployment, and also matches the typical 5 m/sec achieved from a CubeSat P-POD jettison event. Two observations can be made from this figure: the MPS-110 cold gas system is adequate in providing enough ΔV for most 3U CubeSats and some 6U CubeSats for dispersal applications, and the MPS-120 and MPS-130 can be integrated on satellites much larger than CubeSats to gain tactical dispersal capability for low cost compared to custom propulsion system solutions. This is very compelling for missions for smallsats in the range of 50-300 kg that are designed for simple mission
capability and low-cost and where modularity is emphasized or required. Similarly, the MPS-120 and MPS-130 can be used as a modular addition to a deployable ESPA node to create a dedicated stage to capable of delivering multiple CubeSats to a desired orbit and/or phasing.

Missions Requiring Low Flight

Another significant area of interest in the CubeSat community is using low-cost imaging-capable CubeSats to fly at low altitudes to augment the resolution capability of COTS-based imaging systems. This can be employed to support responsive disaster monitoring, localized weather monitoring, and other situations where data from a particular area of interest becomes valuable for a temporary period. To make this concept compelling, significant ΔV is required to counteract drag and extend the lifetime of the satellite to the point where enough data is mined over the life of the satellite to be regarded as worth the cost of an otherwise expendable satellite. This evaluation should also factor in the responsive capability of the CubeSat form factor; a 6-12U imaging CubeSat that is small enough to be integrated with dedicated small satellite launch vehicles or tactical small satellite air-launched platforms could trump the logistical cost of maintaining a constellation of higher-value imaging satellites over longer mission lifecycles which do not necessarily guarantee fast image-capture over a new area of interest. Packageable within a 20 cm x 20 cm x 30 cm volume, these types of CubeSats could be pre-integrated with smaller, dedicated, on-demand launch vehicles sized to deliver spacecraft weighing less than 50 kg to LEO, to be used when other space-based assets are either not accessible or too expensive to utilize. This on-demand capability lends immediate tracking resources to organizations responsible for monitoring disasters like tornados, oil spills, forest fires, etc.

To assure frequent image updates over an area of interest, a low-altitude, repeating ground track orbit can be utilized to provide up to two revisits per day per satellite. Figure 13 below shows such an orbit at 262 km circular, which can provide up to 1.7 m resolution with a COTS type optical system that provides a 9 cm aperture and 1.25 m focal length. Revisit sites over areas of interest for repeating ground track orbits can be easily selected by calculating the required orbital injection site and inclination of the launch vehicle, with the satellite propulsion system conducting the final orbit “cleanup” burns. Image acquisition over multiple areas of interest can potentially be achieved with this system, as Figure 13 demonstrates, to support short and
long-term change detection for global map data, crop management, climate monitoring, etc.

At the altitude of the repeating ground track orbit in Figure 13, the CubeSat Modular Propulsion Systems product line can extend life of 6U CubeSats (baselined weighing 10 kg) with varying ballistic coefficients to the values shown in Table 2. This life augmentation capability provides the end user with frequent and persistent data to support many disaster monitoring and asset protection situations that require dedicated imaging assets over longer time periods.

Table 2: CHAMPS Lifetime Extension at 262 km Circular Orbit.

<table>
<thead>
<tr>
<th>Lifetime (days) for 6U (10kg S/C) at 262 km</th>
<th>MPS-110</th>
<th>MPS-120</th>
<th>MPS-130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballistic Coefficient = 50 kg/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Max</td>
<td>4.5</td>
<td>43.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Solar Nom</td>
<td>11.1</td>
<td>183.4</td>
<td>286.9</td>
</tr>
<tr>
<td>Solar Min</td>
<td>27.5</td>
<td>402.0</td>
<td>626.9</td>
</tr>
<tr>
<td>Ballistic Coefficient = 50 kg/m²</td>
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<td></td>
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<tr>
<td>Solar Max</td>
<td>19.0</td>
<td>169.3</td>
<td>259.9</td>
</tr>
<tr>
<td>Solar Nom</td>
<td>44.0</td>
<td>776.0</td>
<td>1215.9</td>
</tr>
<tr>
<td>Solar Min</td>
<td>109.4</td>
<td>1712.5</td>
<td>2675.1</td>
</tr>
</tbody>
</table>

Figure 13: Low Altitude Repeating Ground Track Orbit Enables High Revisit Rate per Satellite.
Several COTS imaging systems have been identified that can be retrofitted for structural and thermal stability as well as some optical aberrations to provide this resolution capability, while taking up less than 2U of payload space on a CubeSat. Such an optical system that employs either a Maksutov-Cassegrain or Schmidt-Cassegrain telescope mirror system is shown below in Figure 15 for visual comparison to the overall CubeSat form factor.

**Tasking, Processing, Exploitation, and Dissemination**

Tasking, Processing, Exploitation, and Dissemination (TPED) has historically been problematic for imaging missions with high data rates due to difficulty of communicating with available ground stations to guarantee that high-value imaging data is collected and delivered to the end user with acceptable latency. However, recent CubeSat missions have employed deployable high gain antennas to communicate with ground assets with low RF power. Specifically, the AENEAS mission launched a 3U CubeSat that deployed a 0.5m parabolic antenna for communication on WiFi frequencies to ground assets that boasted a gain of +18dB. Other entities are currently developing 2m deployable antennas for S-band communication that occupy only 1U. Advancements in deployables technology continue to mature the possibility of achieving a link from LEO to a dedicated or mobile ground station using burst transmission mode, as well as the possibility of achieving a link to a higher altitude satellite communication network (i.e. TDRSS, etc.) to support frequent high rate data transfer.

High gain deployable antennas also add the potential capability to communicate from higher apogee altitudes, whereby ground stations can be more frequently available for data transmission. With the recent proven capability to deploy CubeSats from the Aft Bulkhead Carrier of the Centaur upper stage on NROL-36, the possibility to deploy CubeSats at GTO has become a reality. Figure 15 shows how this newfound dropoff capability can be used to provide more efficient access to orbits with higher apogees by using propulsion to lower perigee from GTO in order to significantly increase the orbital decay rate until the desired apogee altitude is achieved, whereby an apogee burn is employed to “lock” the orbit by raising perigee back above the high drag regime. With apogee altitudes high enough to enable wide swath paths to access a wide variety of ground stations, with more frequent revisit times, data latency can be improved to support missions with high data downlink rates.

![Figure 14: The MPS-120 provides access to any elliptical orbit from LEO to GTO within a 60 day period when deployed from a GTO drop-off orbit.](image)

![Figure 15: COTS imaging optics can package within CubeSat volumes.](image)
**Constellation Deployment Missions**

Another capability that can enable strategic satellite missions is the ability perform relatively fast phasing maneuvers to quickly deploy a constellation, or “scatter” it. This always comes at a cost impact in the form of propellant consumption, and thus less ΔV remaining for additional necessary maneuvers. Figure 16 below describes the phasing capability for MPS products for a variety of constellations at an orbital altitude of 500km.

**Collision Avoidance Maneuvers**

With space collisions predicted to increase in coming years, CubeSats may be viewed as a contributor to the space debris problem. Due to the non-propulsive nature of most CubeSats launched to date, there is legitimate concern that CubeSats themselves could be a source of space debris that increase the collisions rate, given that they generally cannot conduct propulsive maneuvers to avoid a probable collision predicted by a debris-tracking agency. This concern was recently confirmed to be real with the collision of Ecuador’s...
first CubeSat Pegasus, which is believed to have collided with debris from a Soviet rocket. The MPS-120 provides the solution to this problem by providing the impulse required to avoid probable collisions as well as immediate end-of-life deorbit capability for CubeSats. The result of this is double-edged; it allows CubeSat mission architects to plan missions at higher altitudes, where normally the 25 year deorbit requirement would not be met, and it alleviates the concern from organizations operating high-value spacecraft of unintentional collisions non-maneuverable smallsats. The former effect is demonstrated in Figure 17 below, whereby CubeSats can be deployed to much higher altitudes than would currently be allowed by the 25 year deorbit requirement. Additional detailed information pertaining to this analysis is available at the cited work in the references section. This effect also will drive component manufacturers to produce CubeSat components with increased longevity to meet mission requirements with longer lifetimes enabled by a high-impulse propulsion system.

CONCLUSION

Propulsion solutions are required in order to enable the CubeSat platform to access a variety of new missions including dispersal, low-altitude imaging, and constellation deployment and management, as well as collision avoidance in general to support clean space initiatives. These compelling mission types will strengthen the value proposition of the platform and enable continued explosive market growth. Aerojet is developing the CubeSat Modular Propulsion Systems product line to simplify mission planning, system selection, and satellite integration to the point that any level of CubeSat builder can consider a propulsive mission. Four products are in development with a capability to deliver flight MPS-110 Cold Gas and MPS-120 Hydrazine Monopropellant systems by 2014, MPS-130 AF-M315E Monopropellant systems by 2015, and MPS-160 SEP systems by 2016.
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References


