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INTERNATIONAL SYSTEMS INTEGRATION ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

Over the next few months, the International Space Station (ISS), and human spaceflight in general, will undergo momentous change. The European Columbus and Japanese Kibo Laboratories will be added to the station joining U.S. and Russian elements already on orbit. Columbus, Jules Vernes Automated Transfer Vehicle (ATV) and Kibo Control Centers will soon be joining control centers in the US and Russia in coordinating ISS operations and research. The Canadian Special Purpose Dexterous Manipulator (SPDM) will be performing extra vehicular activities that previously only astronauts on EVA could do, but remotely and with increased safety. This paper will address the integration of these international elements and operations into the ISS, both from hardware and human perspectives. Interoperability of on-orbit systems and ground control centers and their human operators from Europe, Japan, Canada, Russia and the U.S. pose significant and unique challenges. Coordination of logistical support and transportation of crews and cargo is also a major challenge. As we venture out into the cosmos and inhabit the Moon and other planets, it's the systems and operational experience and partnership development on ISS, humanity's orbiting outpost that is making these journeys possible.

INTRODUCTION

In April 1961, Yuri Gagarin spent 1 hour 48 minutes in space. From this first brief step toward the cosmos, humanity is on the verge of establishing a foothold beyond the confines of our home planet. Since Expedition One began on November 2, 2000, the International Space Station has maintained a continuous international human presence in orbit. For about seven years and counting, crew members from the U.S., Russia and Europe have worked, conducted research, exercised, and enjoyed recreation and other activities together in orbit.

International crews have together consumed a total of over 49,000 pounds (22,226 kg) of food. Ground controllers and engineers have coordinated spacecraft systems and operating procedures so that crew and equipment interoperate effectively. Real time spacecraft anomalies have been dealt with and resolved through the valiant efforts of international crew and ground personnel. These lessons learned on ISS in how to integrate machines, humans and systems from several nations will play a key role as human presence is extended to the Moon and Mars.

The International Space Station is a complex undertaking of vast proportions. When complete in 2010, its mass will be about 387 MT, roughly equivalent to the maximum take-off weight of a Boeing 747-400 aircraft (1) or about 241 Lexus ES Luxury automobiles (2). The ISS's pressurized volume of 913 m³ will be greater than that of a five bedroom house or a Boeing 747-400 aircraft and can accommodate about 71 Lexus ES vehicles. The solar arrays, covering an area of 2,192 m², can generate about 708,000 kW-hours of electrical power per year, enough to power about 50 Houston area homes. Major elements will have been built by over 100,000 workers in the U.S., Russia, Canada, Europe, and Japan, and brought to orbit through 35 Space Shuttle assembly flights and 5 Russian launches. Its operations are global. While controllers in Moscow may be enjoying a nice lunch, controllers in Houston will be in the middle of their overnight shift as controllers in Tsukuba may be preparing their dinners.

The development and assembly of the ISS is not only a great technological achievement, but a tremendous management feat. The ISS Partners: NASA, Roscosmos, European Space Agency (ESA), Canadian Space Agency (CSA), and Japanese Aerospace Exploration Agency (JAXA) have broken down communications, cultural and bureaucratic barriers to effectively coordinate and lead the engineering and operations of the largest spacecraft ever constructed. Research conducted on the ISS in the US, Russian, European or Japanese elements will demonstrate Earthly benefits in the medical and physical sciences, and provide a pathway for future exploration beyond Earth orbit.

INTERNATIONAL PROGRAM ELEMENTS

The International Space Station is about 57% complete. Almost all of the supporting structure and systems are on orbit. Very shortly, Node 2 Harmony, the first pressurized element to be launched since the Columbia accident will be attached to the ISS. This module provides the hub for connecting the U.S. Laboratory Destiny with European and Japanese research facilities to be added in the following months.

The addition of Harmony marks a new phase in ISS evolution. With sufficient station structural and physical resources in place, we can now begin the process of incorporating the core International Partner elements. These assembly flights will enable establishment of six-member crew operations and more vigorous utilization of station.

Figure 1 depicts the ISS configuration. The Truss, which provides the backbone structure, power distribution and thermal control systems supporting the pressurized modules, is nearing completion. The port side truss elements are on orbit. The P3/P4 segments were added during the STS-115/12A mission in September 2006. The P6 element, currently attached to the Z0 truss will be moved to its permanent outboard position during the upcoming STS-120/10A mission. The crew of STS-117/13A recently installed the S3/S4 truss segments, deploying its solar arrays and radiators. The short S5 segment was added this summer while assembly of the final S6 truss segment and solar array has been deferred to after assembly of the European and Japanese pressurized elements.

STS-120/ISS mission 10A will temporarily attach Node 2 Harmony to Node 1 Unity, Node 2 will provide the critical connections for subsequent addition of ESA's Columbus Research Laboratory and JAXA's Japanese Experiment Module (JEM) Kibo facility. After the Shuttle departs, Pressurized Mating Adapter 2 will be relocated to the end of Node 2 from its current site at the forward end of Destiny. The combined Node 2 and PMA 2 structure will then be moved to its final location on the forward end of U.S. Laboratory Destiny, where PMA 2 had originally been berthed. This will be the first time a major element will be added without the Shuttle present. Until this work is completed the Shuttle will not be able to dock to the Space Station. This is a huge step forward in autonomous operations and will be a great demonstration of the techniques needed to establish a lunar habitat.

Columbus, weighing about 10 MT before outfitting, is planned for launch this winter. The laboratory, shown in Figure 2, will house an additional 9 MT of equipment including 10 International Standard Payload Racks (ISPR) as well as provide an external payload facility.

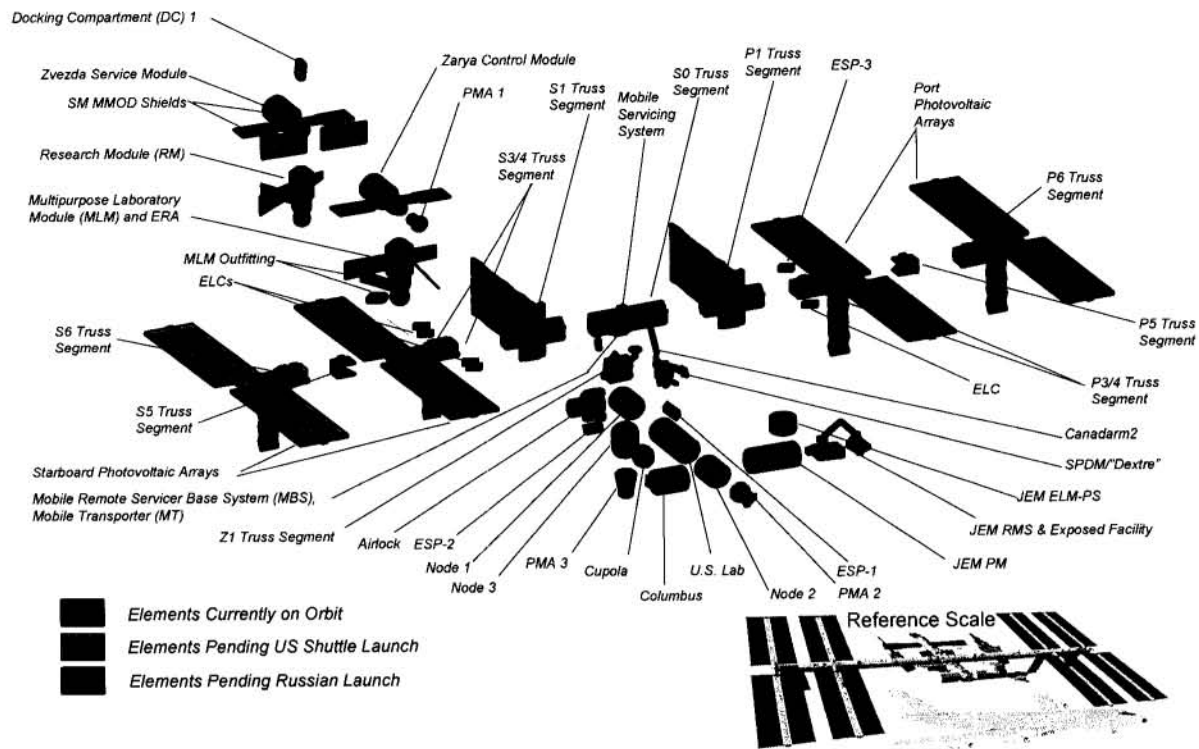


Fig. 1: The ISS Configuration August 2007.

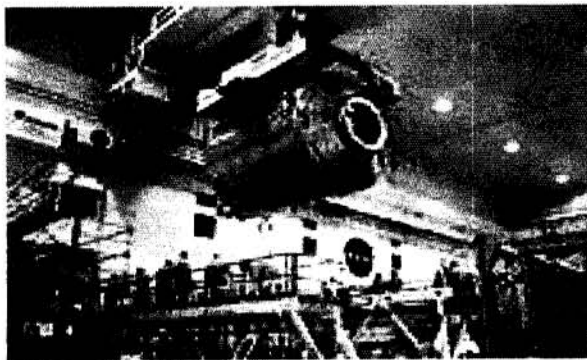


Fig 2: An overhead crane lowers ESA's Columbus Module onto a work stand in the Space Station Processing Facility.

Kibo will be delivered to ISS through three separate Shuttle flights. In early 2008, ISS mission 1J/A will temporarily berth the Experiment Logistics Module (ELM) Pressurized Section (PS), which provides storage for experiments and research equipment, to Node 2 zenith. Shortly thereafter, STS-124/ISS mission 1J will

attach Kibo's Pressurized Module (PM) to its Node 2 port location and ELM-PS relocated to its permanent location atop JEM-PM. JEM-PM is the largest pressurized element on ISS weighing about 16 MT. JEM Exposed Facility (EF) and ELM Exposed Section (ES) will be added to complete the Kibo facility during the third JEM Assembly flight, ISS flight 2J/A.

The JEM research facility will include ten ISPRs. EF will provide ten experiment locations and ES will add three sites exposed to the space environment. These sites are accessible through PM's payload airlock. Exposed experiments could also be manipulated by the JEM Remote Manipulator System (JEM-RMS) launched earlier on 1J. RMS consists of a large six-joint robotic arm with a small fine arm for intricate handling of the exposed experiments. The JEM research facility is shown in Figures 3a, 3b and 3c. The total mass of the entire Kibo research complex is about 27 MT.

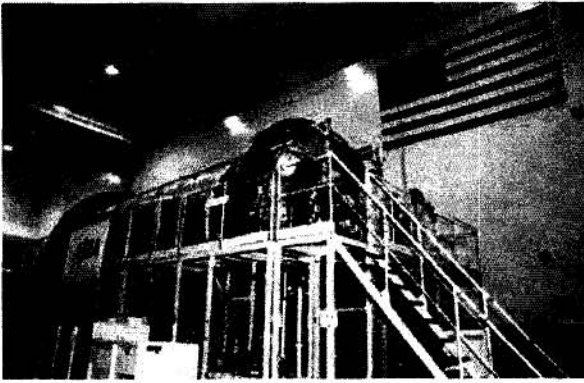


Fig 3a: The Kibo laboratory resides on a stand at the Space Station Processing Facility at Kennedy Space Center being prepared for next year's planned launch.



Fig 3b: The Japanese Experiment Module-Pressurized Section (JEM-PS) arrived at Kennedy Space Center in April 2007 for launch processing.

ISS Mission 1J/A will also deliver the Dextre Special Purpose Dexterous Manipulator. Dextre is part of the Canadian built Mobile Servicing System (MSS). The MSS Canadarm-2 and the Mobile Base System are already on-orbit and being used extensively in ISS assembly. Dextre's dual-arm design will allow it to handle and replace smaller components reducing EVA requirements. NASA's ExPRESS Logistics Carrier is being developed so that its stored spare parts and external mounted experiments will be robotically replaceable by Dextre.



Fig 3c: Workers at Kennedy Space Center attach the Robotic Manipulator System to Kibo. The RMS will be launched with Kibo on ISS Flight 1J next year.

The ISS elements are not stand alone modules but interdependent components of a large, complex spaceship. Structural, electrical power, thermal control, data and voice communications, environmental and life support systems cross international element boundaries. Figure 4 provides an example showing the integration of data communications across the space station local area network through routers in Destiny and Harmony and extending to equipment locations in Columbus and Kibo. The bridge between US and Russian operating segments' networks is accomplished externally and routed through a crew switch panel.

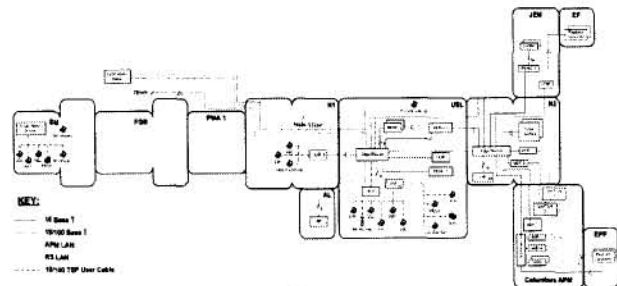


Fig. 4: ISS Integrated Station Local Area Network.

A 2004 New York Times article discussing a new Hewlett-Packard wireless communications device proclaimed that "If your office can't reach you on this, then you must be on the International Space Station (3)." With due respect to the New York Times and through the use of additional security measures; crew members on the ISS are well connected to the world below.

International elements also provide system redundancy necessary for reliable long term operations. Dissimilarly redundant Russian and US carbon dioxide removal and oxygen generation systems, for example, provide assurance that critical life sustaining capabilities can be maintained in the event one system fails for an extended time period.

LOGISTICS SUPPORT

Most cargo supplies are currently brought to ISS by Russian Progress vehicles. There have been about 26 Progress flights to ISS since the launch of Progress 1P in August 2000. Progress typically carries about 2,300 kg of dry cargo, water and air bags, and refueling propellant.

Beginning early next year, additional logistics support will be provided by the European Space Agency's Automated Transfer Vehicle (ATV) shown in Figure 5. ATV will be launched on an Ariane 5 and has capacity to carry about 6,500 kg of dry cargo, water and air bags, and refueling propellant to the ISS. ATV was shipped from the European Space and Technology Center (ESTEC) on July 13, 2007 for launch from the European Spaceport at Kourou, French Guiana.

In a few years, the Japanese Aerospace Exploration Agency's H-II Transfer Vehicle (HTV), shown in Figure 6, will join the ISS logistics resupply effort. HTV is an H-II launched autonomous cargo vehicle with the capacity to carry about 4,900 kg upmass. Most importantly HTV can carry external cargo (cargo destined to be on the outside of ISS). The Canadian built Space Station Remote Manipulator System (SSRMS) will capture and berth HTV to Kibo on the ISS.

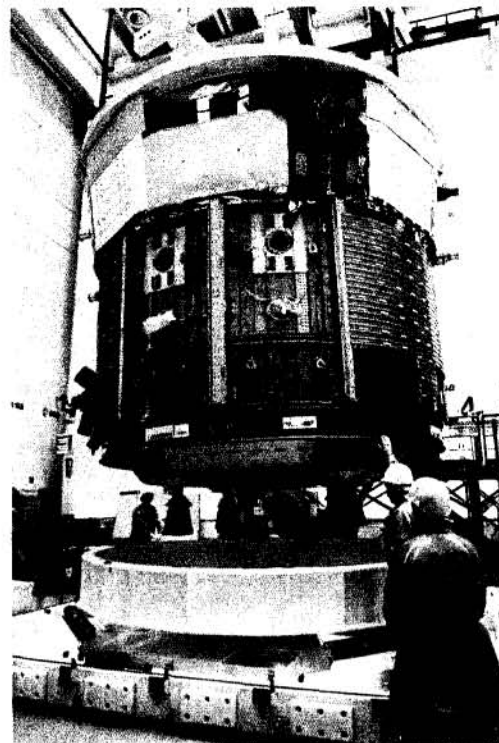


Fig. 5: A Section of the European Space Agency's Autonomous Transfer Vehicle is lowered onto a transportation trolley at the European Space and Technology Center (ESTEC) for shipment to the launch site at Kourou. (Photo: ESA)



Fig. 6: JAXA's H-II Transfer Vehicle (Photo: JAXA)

NASA is also pursuing acquisition of logistics transportation services through commercial US sources. Flight demonstrations are planned for 2009.

CONTROL CENTERS AND OPERATIONS

For the past seven years of continuous ISS operations, ISS operations were coordinated by mission control centers in Moscow (MCC-M) and Houston (MCC-H) with help from robotics control personnel in Saint-Hubert, Quebec, Canada and payload controllers in Huntsville Alabama. Managing the complex interactions and learning to work together, during both routine and unexpected situations, has been a significant challenge.

A good case in point is the experience during the Russian Segment computer anomaly during the ISS 13A mission in June 2007. While the Space Shuttle Orbiter Atlantis was docked to ISS, Service Module Central Computer-2 (LBM-2), shown in Figure 7, went offline followed by three Terminal Computers (TBM-3, TBM-1 and TBM-2) and the remaining Service Module Central Computer lanes (LBM-1 and LBM-3). The loss of these computing systems could have affected the ability of ISS to maintain attitude control through the use of Russian thrusters, the ability of ISS to maintain environmental control through activation of Elektron oxygen generator and Vozdukh carbon dioxide removal system, the ability to maintain thermal control through the external Service Module cooling loops, and power to the Soyuz return vehicle.

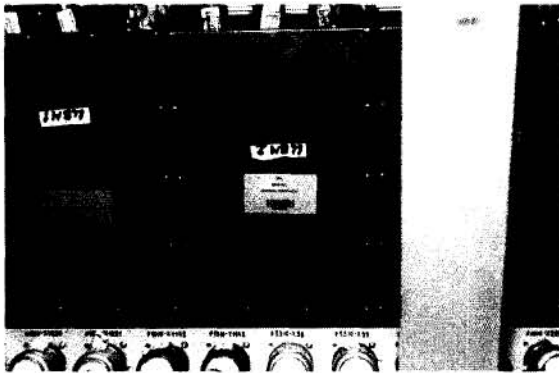


Fig. 7: Service Module Central Computer-2 (LBM-2)

Mission Control Houston immediately started an investigation to determine the relationship, if any, of 13A assembly activities, particularly S3 solar array activation which occurred nearly coincident with the start of the computer anomaly. Concurrent with the MCC-H investigation, Energia, the primary Russian contractor, had formed its own multi-disciplinary team. NASA and Energia teams worked independently to eliminate potential causes and communicated daily. Failure analyses were greatly aided by ESA which proactively provided data and expert personnel familiar with the German-built Service Module Central Computers. The cause was determined to be corrosion found on several connectors which provide command signals to the Central Computers power circuitry.

Operational workarounds were quickly developed to restore Service Module functions. These workarounds required extensive coordination between Russian and US engineers. Further time critical innovative and creative solutions had to be developed to keep the Soyuz spacecraft viable as a return vehicle. No single engineering team had all of the answers or resources to solve this problem. A problem of this nature within a single country or culture is extremely difficult, because the various engineering disciplines must coordinate their work. In this situation, not only did the various engineering functions need to work together, but they had to work together across cultural boundaries. They had to work together and trust the detailed design knowledge from each side. The cooperation was phenomenal and highlights the strength of this international team.

The complexity of communications and coordination will pose a major challenge in the coming years. ISS Control Centers in the U.S., Russia and Canada will soon be joined by the ATV Control Center in Toulouse, France, Columbus Control Center in Oberpfaffenhofen, Germany (shown in Figure 8), and the JEM Control Center in Tsukuba, Japan. Later, the HTV control center, also in Tsukuba, will become operational to support HTV flights. These new human spaceflight operations facilities will coordinate and schedule visiting vehicles, crew activities, and research operations. The complexity of routine interactions, which are currently largely bi-lateral, will sharply increase as

coordination must now occur among all five ISS partners. Impediments of differing operational practices, languages, time zones, and customs must be resolved. ISS Control Center locations are shown in Figure 9.



Fig 8: The Columbus Control Center at Oberpfaffenhofen, Germany will coordinate ESA's ISS operations. (Photo: ESA)

A number of simulations are being conducted in preparation for ATV launch. These mission simulations involve the ATV control center, MCC-H and MCC-M. They help develop operational procedures and coordination as well as provide critical practice for operations personnel.

Similarly, the Columbus Control Center was used to support ESA's Astrolab mission with ESA astronaut Thomas Reiter onboard ISS Expedition 13. This mission provided an opportunity for control center personnel to gain experience in preparation for Columbus activation and routine European operations on ISS beginning later this year.

In 2009, crew size will grow from its current three to six members. The additional crew quarters, galley, waste removal and hygiene capabilities, exercise equipment, crew health care systems operations guidelines and procedures needed to accommodate and support the larger crew size are in development. Plans for crew assignment and rotation are also in work. The increased crew size will allow more opportunity for international partners' expedition crew members.

ISS crews receive some level of cross training on each others equipment, with all members trained in emergency procedures. U.S. crew members acquire a high proficiency in maintenance and operations of U.S. Space Operating Segment (USOS) equipment and are trained as users of Russian equipment. Russian crew members specialize in Russian Space Operating Segment equipment and are trained as users of USOS equipment. An ESA or Russian crew member will be responsible for ATV operations. Each partner is responsible for crew training on its equipment and systems. A training curriculum of two years or longer is typically required (4).

The shared crew training and flight experiences will be invaluable when international crews venture onto lunar or Martian soil. Procedures for routine operations and daily activities, food and recreational preferences, language and personal communications issues, physical and emotional health issues, which may differ among crew members from different parts of the globe, are being worked out on the ISS.

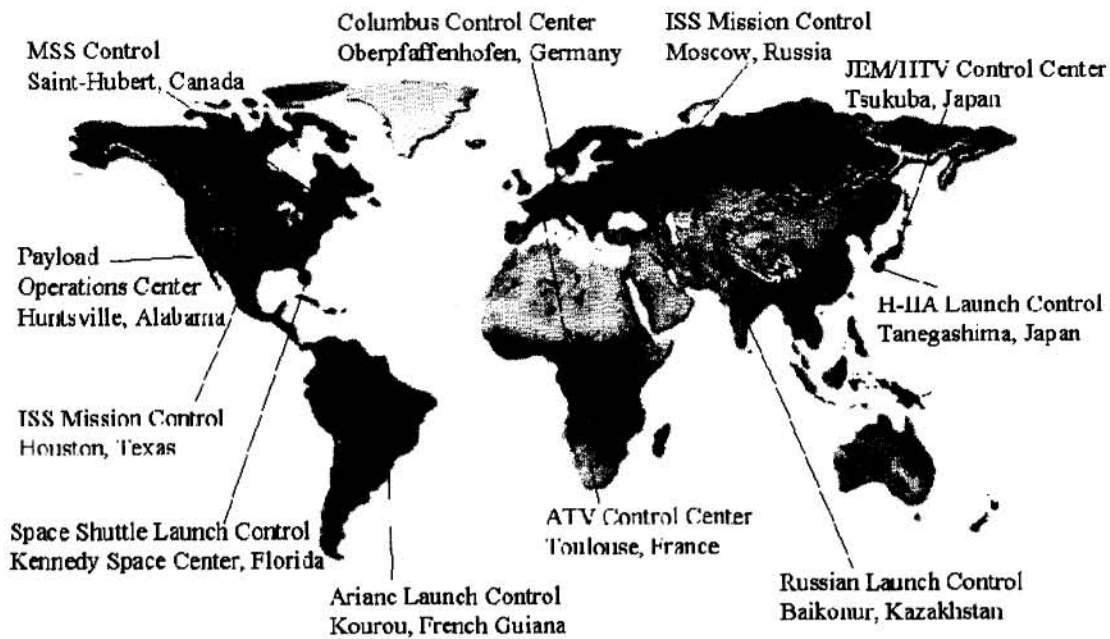


Fig 9: ISS Control Centers are located around the globe.

SUMMARY

The International Space Station is poised to enter a new phase. The next few Shuttle flights will add new elements for human habitation and science research and initiate European and Japanese space and ground based ISS operations. ESA and JAXA activities will be coordinated with on-going American, Canadian and Russian activities. ESA's ATV will begin carrying needed supplies to ISS supplementing Russian Progress resupply vehicles. In the coming years, JAXA's HTV will join the ISS space vehicle support fleet. When taken together, the station will be a very busy transportation and research hub, with a correspondingly active and complex ground support and control infrastructure. Developing and operating these systems from the U.S., Russia, Europe, Japan and Canada are providing a live and vigorous testbed for future multi-national exploration of the moon and Mars. The International Space Station will help to insure the success of humankind's future exploration into the galaxy.

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