

Ground operations demonstration unit for liquid hydrogen initial test results

W U Notardonato¹, W L Johnson², A M Swanger³ and T Tomsik²

¹NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899 USA

²NASA Glenn Research Center, Cryogenic and Fluids Branch, LTF0, Cleveland, OH 44135 USA

³NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-M5-B, KSC, FL 32899 USA

Abstract. NASA operations for handling cryogenics in ground support equipment have not changed substantially in 50 years, despite major technology advances in the field of cryogenics. NASA loses approximately 50% of the hydrogen purchased because of a continuous heat leak into ground and flight vessels, transient chill down of warm cryogenic equipment, liquid bleeds, and vent losses. NASA Kennedy Space Center (KSC) needs to develop energy-efficient cryogenic ground systems to minimize propellant losses, simplify operations, and reduce cost associated with hydrogen usage. The GODU LH2 project has designed, assembled, and started testing of a prototype storage and distribution system for liquid hydrogen that represents an advanced end-to-end cryogenic propellant system for a ground launch complex. The project has multiple objectives including zero loss storage and transfer, liquefaction of gaseous hydrogen, and densification of liquid hydrogen. The system is unique because it uses an integrated refrigeration and storage system (IRAS) to control the state of the fluid. This paper will present and discuss the results of the initial phase of testing of the GODU LH2 system.

1. Introduction

NASA operations for handling cryogenics in ground support equipment have not changed substantially in 50 years, despite advances in the field of cryogenics. NASA typically loses 50% of the hydrogen purchased[1]. Since hydrogen production, liquefaction, storage and transfer is an energy intensive process, this represents a large quantity of energy lost. The Shuttle Program's cost for cryogenic propellants for Stennis Space Center and KSC was over \$20M per year between 2006 and 2009. This number represents a mature program with minimal engine testing and a low annual flight rate. NASA needs to develop energy-efficient cryogenic ground systems to minimize propellant losses, minimize the size of new storage tanks, simplify test and launch operations, minimize helium consumption, and reduce the environmental impact of the space program. The GODU LH2 project was conceived to demonstrate advanced cryogenic operations that minimize capital and operations cost, including power, system size, lost consumables, and manpower. It is hoped that successful demonstration of these energy efficient cryogenic operations in a relevant scale and environment will enable their incorporation in future spaceport architectures. The system design is also relevant to a number of low temperature energy systems, hydrogen fueling infrastructure for transportation applications, and in situ resource utilization efforts on the Moon or Mars.

Although NASA was one of the drivers of the development of large scale LH2 systems, commercial industry has since passed us by. The state of the art in cryogenic systems has advanced greatly in the

past 50 years, especially in the field of cryogenic refrigeration. Hydrogen temperature refrigerators are available for a wide range of capacities and these refrigerators are critical to achieve active thermal control of the cryogen. Depending on the refrigerator capacity, this system can be used for zero boil off storage, in situ liquefaction, or propellant conditioning/densification. This Integrated Refrigeration and Storage (IRAS) concept allows liquid hydrogen to be stored in a quasi-equilibrium state. The simplest example of this is a zero boil off system (ZBO). The IRAS concept is novel in that it cools the liquid directly at the storage site and is designed to operate with refrigerator capacity to system heat leak ratio ($R = Q_R/Q_{HL}$) greater than 1. Continuous operation of the cryogenic refrigerator minimizes the overall refrigeration capacity required and increases reliability compared to systems designed to operate intermittently. Cooling the liquid directly allows for control of the bulk temperature of the fluid as opposed to pressure control of the ullage using vent and relief valves. This also enables easier depressurization of tank ullage pressure and bulk fluid conditioning for greater vehicle loading control. Conditioning operations can also serve as a store of refrigeration energy for load balancing. Higher Q_R/Q_{HL} ratios allow for advanced operations such as propellant densification and liquefaction, and future spaceport and test center architectural visions culminate with a distributed production capability to individual pads for liquefaction and zero loss storage and transfer. For these systems, launch customers will only be billed for hydrogen after it crosses the flight to ground umbilical, not what gets purchased hundreds of miles away many months before launch.

The ability to actively control the thermodynamic state of the liquid hydrogen via refrigeration for spaceport applications is a new concept, and there will be a learning curve associated with implementation. Previously the concept has been proven at the 180 liter scale using a Gifford McMahon cryocooler in a partnership with the Florida Solar Energy Center [2]. Storage and handling characteristics have been evaluated as the hydrogen volume increased from empty to 90% full via in situ liquefaction. Pressurization and depressurization cycles at various liquid levels were performed, and data was collected on thermal stratification. The system behavior was understood and testing at a more relevant scale in an operational environment is the next step. The GODU LH2 project has designed, assembled, and is testing a prototype storage and distribution system for liquid hydrogen that represents a complete end-to-end cryogenic propellant system for a ground launch complex. The project has multiple related objectives and will culminate with an advanced operational demonstration of the loading of a simulated flight tank with densified propellants. The system is unique because it uses an IRAS system to remove heat leak and thermal energy from the fluid. The integrated refrigerator is the critical feature enabling the control of the propellant state.

The overall goal of the project is to demonstrate efficient LH2 operations on a relevant scale that can be projected onto future Spaceport architectures. This goal will be demonstrated by completing primary test objectives in the area of efficient and reliable integrated liquid hydrogen systems. There are three primary test objectives for GODU LH2. These are

- I. Demonstrate zero loss storage and transfer of LH2
- II. Demonstrate hydrogen densification in storage tank and loading of a flight tank
- III. Demonstrate hydrogen liquefaction using close cycle helium refrigeration

Zero loss storage and transfer

Past studies detailed loss mechanisms in historical shuttle data. Replenishment inefficiency, from the tanker at the point of purchase to delivery in the launch site storage tank, accounted for 26% of the losses. Normal evaporation (boil-off) in the storage tank between launches/tests was another 24%. Ground losses (chill down) during propellant loading or scrub operations accounted for 15%. And flight tank losses during propellant loading or scrub operations were the largest contributor with 35%.

The system is designed with refrigeration capacity will be sized to allow for zero boil-off storage in the tank, reliquefaction of vapors normally lost in the chill down of transfer lines, reliquefaction (instead

of venting) of ullage gas used for pressurization, and all losses from tanker operations. This system will attempt to demonstrate techniques to recover 65% of the hydrogen lost today.

Propellant densification/conditioning.

Densified propellants that are subcooled below their normal boiling point enable minimized vehicle size, increased payload mass fraction, and extended loiter time before the onset of venting of in-space storage. Densified propellants have been identified as a promising option for increasing the performance of chemical propulsion systems and were considered for the Space Transportation System (STS), X-33, National Aerospace Plane (NASP), and the Second Generation Reusable Launch Vehicle (RLV) programs. Excessive complexity of the associated ground systems and limited ground operations experience were factors that hampered the adoption of densified propellants in earlier programs. The integrated refrigeration and storage approach has been identified to be a simple, reliable, and efficient method of producing densified propellants. This has applications in other LH2 transport systems as an energy storage medium. Thermal control and pressure control issues associated with the flight tank loading process must still be resolved in addition to building an operational experience base using a full-scale system. With integrated refrigerators, advanced insulation, and novel pressurization schemes, densified hydrogen will be loaded into a simulated flight tank, thermal stratification will be measured and controlled, and a target bulk propellant temperature of 16.5 K in the flight tank will be demonstrated.

Liquefaction

The optimal solution to reduce hydrogen losses at the launch site may involve local production and liquefaction. Industrial gas companies are organized to meet the needs of other customers, and the unique needs of the space industry are not being met efficiently with the current infrastructure. Small-scale liquefaction operations (50 gallons per day) will be demonstrated in GODU LH2, and the system can be modified to increase performance as needed. Using a central hydrogen production plant with pressurized GH2 pipelines to individual pads would allow on mass input to a liquefier and the refrigerator liquefies 100% of the incoming stream. With a hydrogen turbo-alternator in line, the compression energy at the production plant can be partially recovered by the expansion process.

2. System Design

The GODU LH2 system consists of these major subsystems: storage tank, refrigeration system, transfer and vent systems, pneumatics, command and control/instrumentation, and facility site and safety preparations. These are described in more detail below.

The IRAS tank is a 125 m³ vacuum jacketed vessel with multi-layer insulation, three liquid ports, one vent port, one cold gas supply port and several smaller sense lines. The liquid ports are used for filling and vaporizer supply, liquid supply to the flight tank, and a spare for future test possibilities. The vent port accommodates pressure relief valves, manual and remote vent valves, and pressurization legs from the pneumatic and vaporizer systems. The IRAS tank has a manway on the top with a bayonet plug that has been modified to allow for refrigerant line penetrations for GHe flow into and out of the inner tank to the submerged heat exchanger coil. The HX coil was designed to promote maximum refrigeration heat transfer and distributed cooling in the tank. The manway also has a cold gas supply port for GH2 inlet from the liquefaction leg and the HETL return leg. The inner tank will also be modified to allow for temperature sensing in the liquid region. Structural modifications were needed to allow the tank to withstand subatmospheric operations. Nine internal rings were added to provide stiffness in the event of an inner tank vacuum and a loss of vacuum in the annulus. Details of the IRAS tank design and construction have been previously published [3].

The cryogenic refrigerator is the critical component needed for this system. An 850 W at 20K Brayton cycle refrigerator, manufactured by Linde, has been procured for this project. The refrigeration system is located inside a standard ISO shipping container for portability and the entire container is purged with outside air to prevent the system from being exposed to hydrogen gas. The refrigerator provides cooling

to the inside of the IRAS tank by means of a cold gas circulation system. The cold helium absorbs heat leak from the stored liquid hydrogen via a submerged heat exchanger. Additional heat is absorbed in the transport lines and thru the active components. This heat is then rejected by the cryocooler to a chilled water circulation loop.

The gaseous and liquid transfer subsystem includes all lines, valves, and supports required to flow liquid hydrogen from the tanker supply to the main storage tank, from the storage tank to the simulated flight tank, and the gaseous hydrogen from these systems to the vent and flare systems.

To reduce project cost, several pneumatic panels and gas storage bottles were reused from the shuttle program to provide gaseous helium, hydrogen and nitrogen to the system. Two 16.5 mPa psi movable storage units (MSU) provide a 2265 m³ helium storage capability, and three additional 16.5 mPa MSU's store up to 3400 m³ of gaseous nitrogen. Gaseous hydrogen is supplied to the site by compressed gas trailers. The facility nitrogen panel reduces the 16.5 mPa down to several 5 mPa sources as well as up to twenty 700 kPa sources used for valve actuation, panel inerting, and purging of lines. Gaseous hydrogen is regulated from 25.5 mPa down to 1030 kPa and is used for liquefaction supply as well as purge and pressurization of lines and tanks.

The command and control and data and acquisition system will use commercial Allen Bradley PLC and interface modules. Numerous control loops will be programmed to control refrigeration capacity, liquefaction rates, transfer and replenish flow rates, and system pressures. This subsystem also includes the necessary hazardous gas and fire detection systems as well as video cameras. Advanced instrumentation, including real time composition measurements, will be developed and tested in the system operation. The C&C system for the initial testing will not use any advanced features such as autonomous control or fault detection, isolation, and recovery.

The control system will operate the refrigerator in two different modes which are defined as zero boiloff (ZBO) mode and the densification mode. Zero boiloff mode regulates the internal refrigerator trim heater to adjust total capacity based on a control signal that reads either the IRAS tank pressure or bulk fluid temperature. When the IRAS tank pressure/temperature is above the set pressure, the refrigerator increases output causing the tank pressure/temperature to decrease. When the IRAS tank pressure/temperature is below the set pressure, the refrigerator output decreases and ambient heat leak causes the tank pressure/temperature to increase. Due to the unknown tank heat load, it is not known if the LN₂ pre-cooling system will need to be operated while the refrigeration system is in ZBO mode.

The refrigerator operates at full power mode during propellant densification and liquefaction test operations. The control signal to the refrigerator always requires the refrigerator to operate at 100% capacity with LN₂ precooling. During densification operations, the IRAS tank pressure will decrease until it reaches a system equilibrium temperature where the refrigeration power will equal the heat load on the tank and refrigeration system. The estimated minimum temperatures for the system are 16.5 K. During liquefaction operations, the refrigerator operates at full power, but the tank pressure will be controlled by regulating the gaseous hydrogen inlet flow rate using the liquefaction mass flow controller (MFC). The incoming hydrogen gas flow stream can be pre-cooled in a liquid nitrogen heat exchange in addition to flowing through an ortho hydrogen to para hydrogen conversion catalyst bed.

The M7-0912 facility, and the adjacent field to the east, have been approved by the Facility Management Board as the GODU LH₂ test site. Facility modifications were performed to provide necessary power to the field. A 500 KvA transformer is used to step down the 13.2kV power supply to 480V required by the refrigerator and chiller. A secondary 75KvA transformer reduces the 480V power to 120/208V for command and control and instrumentation purposes. The control room is a trailer located 500 feet away from the tank inside a 100' x 100' metal clamshell building. The clamshell also serves as the staging area for equipment, and has a small machine shop for working on fabrication of tubing, conduit, and structural systems. An overall view of the test site is shown below in figure 1.

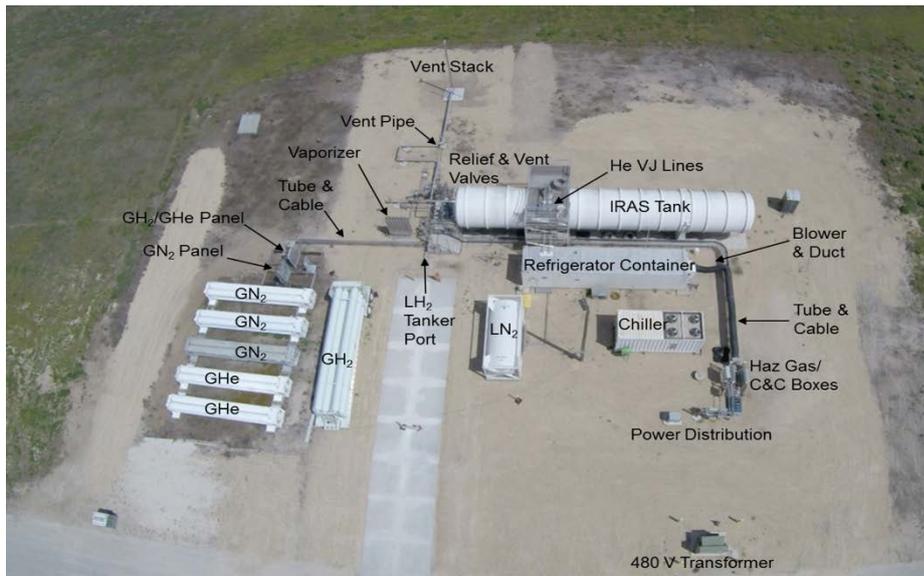


Figure 1: Test site overview

3. Test Operations

Verification and validation testing of the system was completed by the end of February 2015 and final OK to start testing was given in the beginning of March. First, remaining liquid nitrogen from the cold shock test, was drained from the tank and the remaining gas was evacuated with a vacuum pump. Several pulse purge cycles were performed to remove the remaining gaseous nitrogen and replaced it with gaseous hydrogen. Purging continued until the hydrogen purity was above 99.95%, with the remaining contaminants being nitrogen, oxygen and water vapor. Unfortunately these purge cycles caused the tank to warm up to ambient temperature. A zero loss tanker offload to a warm tank is more difficult, so the refrigerator was turned on and used to chill down the tank wall by cooling the gas inside the tank.

The chilldown process started on March 9 when refrigeration was turned opened to the tank. The tank was locked up with 50 psi GH₂ inside. Over the next 5 weeks, the tank temperature and pressure slowly decreased. Hydrogen needed to be added five times during the process as the tank pressures decreased to near atmospheric level. Several issues arose during the chilldown process causing delays in the overall timeline. First, two power outages due to weather events shut down the refrigerator. Later, a vacuum leak in the helium VJ line leading to the tank caused the bayonet seals to cool down and leak helium refrigerant. Troubleshooting and subsequent re-servicing and clean up cycles caused a week delay. There were also issues associated with a leaking refrigerator valve causing warm helium to bypass the HX and pistons, drastically reducing the capacity of the refrigerator. Final conditions inside the tank indicated there was liquid droplets forming on the HX tubes. At this point the first GH₂ trailer was empty and a liquid tanker was brought in to start the zero loss tanker operations. Figure 2 shows the tank temperatures during the chill down process. Power outages are identified by the data drops, and hydrogen gas refill operations show temperature spikes. The eight day delay due to a leaking helium joint shows the actual chilldown probably was achievable in less than a month.

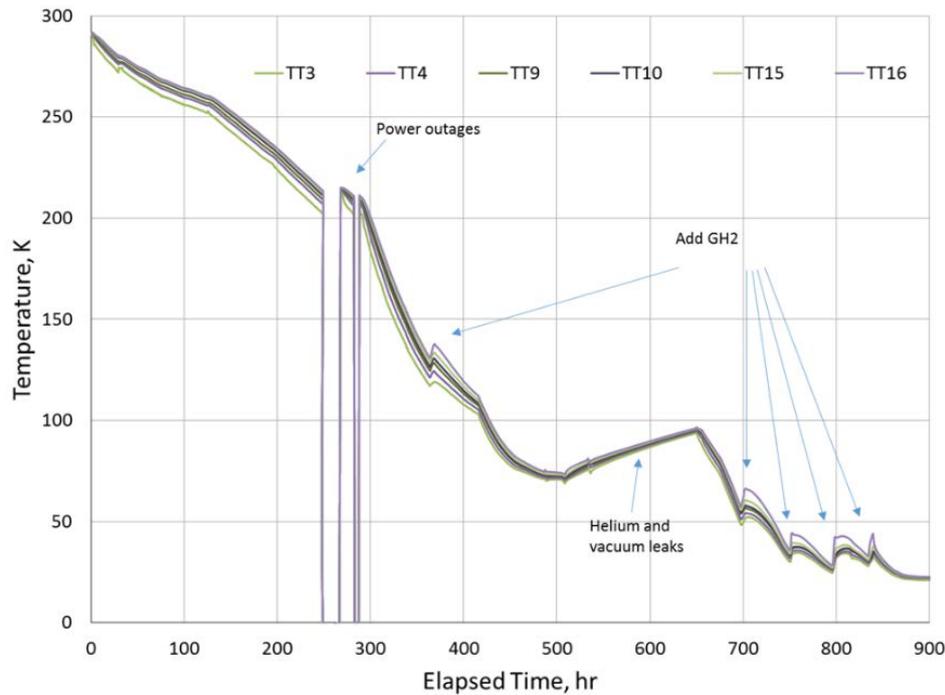


Figure 2) Tank temperatures during chilldown

After successful zero loss chilldown, the first LH2 tanker no-vent fill off-load test that was conducted on May 21st. Approximately 11,800 gallons of LH2 was transferred from a Praxair roadable trailer into the 33,000 gallon test dewar in an elapsed time of 1 hour and twenty-four minutes using a no-vent fill process. Since pressures remained below the maximum cut-off value, no product venting during the LH2 trailer off-load test was required during LH2 transfer to the test tank. The initial and final pressures inside the test dewar were 21 psia and 50 psia, respectively, representing a total pressure rise of 29 psi. During the operation, the cryogenic refrigerator was non-operational but because initial tank wall temperatures ranged from 55 – 64 K and were very cold, that amount of pre-chill of an empty tank enabled the no-vent fill to occur without exceeding the pressure limits established for the system and the need to vent. Pre-test analysis of the tank with an all GH2 ullage system confirmed that the no-vent could occur. This major milestone represents the first successful planned test to demonstrate the new technology for LH2 storage. Figure 3 shows the liquid volume in the tank and the tank pressure during the tanker offload. Liquid volume is shown by delta-p measurements as well as a totalizer flow meter on the tanker.

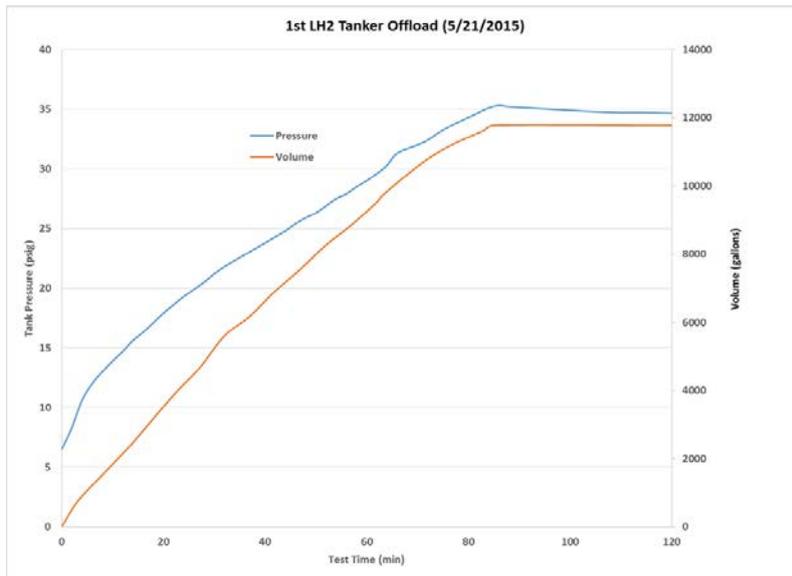


Figure 3) Liquid volume and tank pressure during tanker offload.

The refrigeration system had been turned off for about five days prior to the tanker offload, and was not operating during the tanker offload itself. In the future the refrigerator will be operating during these transfers to minimize tank pressure and remove energy during the offload process. In this case, the tank was locked up for 30 hours after the offload. At first ullage pressure decreased as the liquid and gas sought equilibrium. Then the heat leak in the tank started to cause a pressure increase. The refrigeration system was restarted on May 22 with LN2 precooling. The system pressure and temperatures immediately started decreasing. The ullage pressure decreased within 10 hours to the saturation point. The bulk fluid temperature and pressure continued to decrease over the next 4 days until the LN2 precooling was turned off with the tank at 5 psig. This test demonstrates the ability to control the state of the propellant by removing energy from the tank via refrigeration as opposed to removing mass by venting. This allows for greater control that is not dependent on the atmospheric pressure and does not lose product. The higher the refrigeration ratio the higher the amount of control you have over the propellant. Figure 4 below shows the IRAS tank pressure and average tank temperature during the depressurization process.

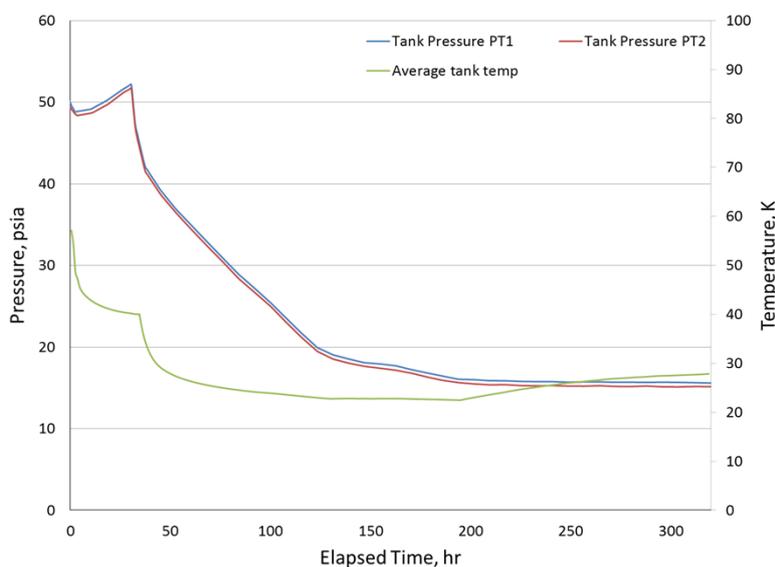


Figure 4) Tank pressure and temperature during depressurization

4. Conclusions

NASA Kennedy Space Center has built and started testing a ground operations demonstration unit for liquid hydrogen to demonstrate advanced storage and distribution operations compared to typical KSC processes. Test operations have just started. The system was chilled down over time using refrigeration power. A liquid hydrogen tanker was offloaded in a no vent fill process. The heat from the tanker fill process was removed from the tank using the refrigerator and the system pressure was controlled and decreased. Boil off heat leak testing is ongoing with preliminary heat leak estimates being 270W.

References

- [1] Partridge, J. K., "Fractional consumption of liquid hydrogen and liquid oxygen during the space shuttle program," *Advances in Cryogenic Engineering, AIP Conference Proceedings*, Vol.1434, pp.1765-1770 (2012).
- [2] Notardonato, W.U., Baik, J.H., McIntosh, G.E., "Operational testing of densified hydrogen using G-M refrigeration", *AIP Conference Proceedings* 06/2004; 710(1):64-74. DOI: 10.1063/1.1774668