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Background, Current Status, and Prognosis of the Ongoing Slush Hydrogen Technology Development Program for the NASP

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BACKGROUND, CURRENT STATUS, AND PROGNOSIS OF THE ONGOING SLUSH HYDROGEN TECHNOLOGY DEVELOPMENT PROGRAM FOR THE NASP

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Abstract

Among the Hydrogen Projects at the National Aeronautics and Space Administration's Lewis Research Center, (NASA Lewis), Cleveland, Ohio, U.S.A., is the task of implementing and managing the Slush Hydrogen (SLH_2) Technology Program for the United States' National Aero-Space Plane Joint Program Office (NASP JPO). The objectives of this NASA Lewis program are (1) to provide verified numerical models of fluid production, storage, transfer, and feed systems and (2) to provide verified design criteria for other engineered aspects of SLH_2 systems germane to a NASP. The pursuit of these objectives is multi-dimensional, covers a range of problem areas, works these to different levels of depth, and takes advantage of the resources available in private industry, academia, and the U.S. Government.

This paper is a summary of the NASA Lewis overall SLH_2 program plan, its implementation, the present level of effort in each of the program areas, some of the results already in hand, and the prognosis for the effort in the immediate future.

1. INTRODUCTION

Just about 2-1/2 years ago the United States' National Aero-Space Plane Joint Program Office (NASP JPO) gave the NASA Lewis Research Center (NASA Lewis) the task of structuring and then beginning the implementation of a path whereby slush hydrogen (SLH_2) could be sufficiently characterized so as to make it useable as the fuel-of-choice for a single stage to orbit (SSTO) vehicle. The reason for consideration of SLH_2, a mixture comprised of the solid and liquid states of the element, as a fuel for aerospace applications lies basically in its increased density and its increased heat capacity relative to normal boiling point (NBP) liquid hydrogen (LH_2).

Figure 1 displays the statepoints of NBP LH_2 and of 50 percent solids content SLH_2. Relative to the heat of vaporization at one atmosphere we can have an enthalpy gain of 11.5 percent of sensible heat by going to the triple point (TP) and an enthalpy increase of as much as 18.1 percent of sensible plus latent heat by continuing to a 50 percent solid-liquid mixture. With regard to density, an increase of about 9 percent can be achieved by dropping the temperature of the hydrogen to the TP, or an increase of about 16 percent can be achieved by going all the way to the 50 percent quality statepoint in the solid-liquid region. Using the more dense SLH_2 rather than NBP liquid as the cryogenic working fluid will yield reduced vehicle size with a corresponding decrease in vehicle weight. The benefits are compounded by a factor of between 2 and 3 due to the associated reductions in both cooling and propulsion requirements as the vehicle size is reduced. The benefit has been quantified as being between a 13 and 26 percent savings in the gross takeoff weight (GTW). As can be seen the economic advantage of using SLH_2 is well worth the effort. In fact, the gain afforded using SLH_2 is in the same range as that anticipated due to the use of the advanced materials presently being developed by five of the U.S. aerospace companies.

By way of structuring the path which an evolving task could follow NASA Lewis postulated the six major groups of jobs seen in Fig. 2. When these job categories were being developed, major consideration was given from an economics and a scheduling standpoint to the recognition of the difference between technology-type work and applications-type work. Each one of the postulated categories in Fig. 2 was further partitioned with the philosophy that a orderly unfolding of effort is generally comprised of analysis followed by experiment which, in turn, results in engineering conclusions. The partitioning resulted in the specification of items which fell into either an "experiment," an "analysis," or a "study" category. Analysis work is part of the first four groups of the program; technology work will be accomplished as part of the first two groups. Experimental work is laced throughout all six groups. In the fourth and fifth groups all the experimental work is directed at verification of the anticipated designs. Lastly, it was implicit in the planning that safety issues would be treated within each group, but an overall "across the board" safety effort was also needed so as to generalize the work. In a nut-shell then, the approach is to conduct analytical studies, where possible, which will help to define the technology problems, conduct the experimental work required for design methodology verification as well as for verification of "analytical models," and then use the resulting "tools" and data to investigate the NASP application employing "proof-of-concept" (POC) hardware. A complete documentation of this plan can be found in Ref. [1].

The resulting Task Plan is being implemented using engineering resources available in (a) the aerospace industry, (b) the cryoservices industry, (c) the academic institutions, and (d) the U.S. Government. Figure 3 is a pictorial arrangement of the different types of work that are on-going and what particular group is engaged in what effort. This chart is an evolving picture both from the participant and the work objective standpoint. It is a "living" chart, things at this point are mainly being added to it subject-wise. In this conference you will have already been exposed to the NASP JPO techniques of (1) "teaming" between the nongovernment corporations (i.e., elimination of competition) and (2) "work packages" aspired to and in a way "contracted for" by performing organizations such as private industrial consortium groups and/or by U.S. Government testing centers. Both these techniques will begin to be realized in the next fiscal year. As a result, further partitioning of the work efforts in the SLH_2 area is both anticipated and expected. For the present, however, this paper will be concerned only with discussion of the current year update of the NASA Lewis managed program and the prognosis for some of the future work. The status of the program as it existed 1 year ago was presented at the 1989 Cryogenic Engineering Conference in Los Angeles, CA (Ref. [2] or [3]).

2. CONTRACT WORK - THE SLUSH TECHNOLOGY FACILITY

Over the course of this last year the McDonnell Douglas Space Systems Company (MDSSC) and their subcontractors, the Martin Marietta Astronautics Group (MMAG) and Air Products and Chemicals Incorporated (APCI), have brought the assembly of a large scale SLH_2 Test Facility (STF) to an operational readiness status. The immediate specific test objectives of this facility are to obtain; (a) data on methods and rates of SLH_2 formation using the evaporative cooling method, (b) definition of some selected flow characteristics of SLH_2, (c) investigatory data on pressurization of SLH_2 tankage, and (d) exploratory data and performance data on selected pieces of instrumentation usable in SLH_2 systems.

A diagram of this facility is given as Fig. 4, and a photograph of it as Fig. 5. The major subsystems of the STF are (1) a SLH_2 generator, (2) a 2700 cfm vacuum pumping system, (3) a 500 gallon test tank, (4) a vacuum jacketed line transfer subsystem, (5) a recycle triple point tank, and (6) a subscale test installation. A 12,000 gallon LH_2 storage and supply tank is also incorporated into the STF. The 1300 gallon SLH_2 generator, in conjuction with the vacuum pumping system, will use the evaporative cooling method to successively produce 700 gallon batches of slush hydrogen. The SLH_2 generator and the recycle triple point tank are thermally insulated by a vacuum annulus in which is a radiation shield cooled to LN_2 temperature. The 500 gallon test tank is insulated by a 12-in. minimum evacuated annulus filled with Perlite. All slush or liquid transfer lines are vacuum jacketed and of welded construction.

Within the resources available the design criteria for the STF were made as general as possible to maximize the functionality of the installation. After production, a batch of SLH_2 can be transferred into the 500 gallon test tank where it can (1) be experimented upon such as in selective pressurization tests or in solids-content upgrading by additional evaporative cooling, (2) be pressure or pump transferred to a receiver tank (i.e., recycle triple point tank) through a "run" into which test hardware such as other tanks or flow components have been inserted for experimentation, or (3) transferred into the subscale test installation comprised of several vacuum-jacketed glass Dewars and be experimented upon there before being dumped into the recycle tank. Finally, all hydrogen propellant collected in the recycle tank can be transferred back into the SLH_2 generator for reprocessing or subsequent return to the 12,000 gallon storage tank.

Two of the subsystems of the STF have already, as part of other programmatic actions, been exercised with SLH_2. Within the subscale test installation the first action involved one of the 20 gallon capacity glass Dewar vessels which was used to explore development of a repeatable procedure for producing SLH_2 having good solid fraction via the evaporative cooling process. Evacuation rate, cycle time, time between subsequent cycles, and total number of cycles in a batch production process were all looked at. A complete set of the data resulting from this work has been compiled, put into report form, and is ready for release as a NASP report (Ref. [4]). The second action involved the 500 gallon test tank which was used to conduct several pre-expulsion tank pressurizations, and some propellant expulsion activity, using different pressurant gases. Initial tests were made using only cold GHe, subsequent to that were tests using only warm GH_2, and finally some tests using cold GHe to bring the tank ullage up to the desired pressure level followed by warm GH_2 to expel some of the cryogenic propellant. Results noted were the rate of pressurant gas flow, pressure stability within the tank under all phases of a pressurization-expulsion cycle, and any seeming benefit with a cycle using a menu of two different pressurant gases. A complete set of the data resulting from this work has been compiled and is available as Ref. [5].

Programmatically speaking, the uniqueness of this facility will allow efficient conduct of future testing in the following categories: (1) propellant loading and upgrading, (2) evaluation of internal tank hardware such as "spraybars" for liquid or gas, (3) SLH_2 solid fraction quality maintenance techniques, (4) hydraulic, pneumatic, and instrumentation prototype subsystem evaluation, and (5) major flow subsystem component testing.

3. INTERAGENCY WORK - NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Over the course of this last year the National Institute of Standards and Technology has brought the assembly of their large scale test facility to an operational readiness status as well as exercised it with SLH_2 testing. The immediate specific test objectives of this facility are to obtain; (1) data on methods and rates of SLH_2 formation using the helium refrigeration method, (2) head-to-head comparison of the helium refrigeration method and the evaporative cooling method in the same generator tank, (3) obtain operational data on the fragility of SLH_2 when moved via a pump through different head-rise budgets at different flow rates, (4) operational evaluation of several critical pieces of instrumentation needed for future work with SLH_2 systems (no matter their size), and (5) provide data on selected safety issues and questions such as SLH_2 degradation due to "propellant contamination"

A diagram of this facility is given as Fig. 6, and a photograph of it as Fig. 7. The major subsystems of the N.I.S.T. installation are (1) a SLH_2 generator tank nominally of 200 gallon capacity, (2) a 2400 cfm vacuum pumping system, (3) a liquid helium closed-loop 1 kW refrigeration system which serves an in-generator mounted freezing surface for hydrogen propellant, (4) a vacuum-jacketed transfer line subsystem which both emminates from and returns to the generator tank, (5) a submerged 100 gpm SLH_2 centrifugal pump for use in moving the propellant through the transfer line, and (6) a 4-ft × 3-ft × 2-ft rectangular parallelopiped enclosed test section which is used to insulate but yet allow continuous viewing of test articles in the transfer subsystem during SLH_2 flow periods. During test run periods LH_2 is brought into the facility area in a roadable Dewar. The 185 gallon SLH_2 generator can be used with the vacuum pumping system to produce SLH_2 by evaporative cooling or it can be used with the liquid helium closed-loop refrigeration system to produce solid hydrogen by freezing triple point liquid on a heat exchanger surface inside the generator. In the flow loop all slush or liquid hydrogen transfer lines are vacuum jacketed and of welded construction.

As with the generator tank in the STF, and which is also true for the generator tank at the NASA Lewis K-Site Facility (see below), the internal volume of the N.I.S.T. tank can be visually monitored during all operations. Also, the density changes of the cryogen within the tank can be determined by transducers which employ nuclear resonance attenuation. After production of a batch of SLH_2 by either the evaporative cooling method or the helium refrigeration technique the propellant can be pumped into the vacuum-jacketed transfer line subsystem. Experimentation can then be performed on any test hardware apparatus inserted in the test section box.

The technique of production for the manufacture of large quantities of SLH_2 for possible use with NASP is still a matter of significant concern. To design large scale systems to produce and utilize hundreds of thousands of pounds of SLH_2 for a single stage to orbit (SSTO) application requires process data which is much more complete than what now exists. From an engineering standpoint there is not yet sufficient data in existence to begin a study of manufacturing SLH_2 in the quantities needed by a NASP. The N.I.S.T. test installation has been exercised with SLH_2 and has begun to acquire the information needed in this category of endeavor. Figure 8(a) displays the increase in solid fraction for a test batch of SLH_2 made using the evaporative cooling method. Within a few hours the batch was completed, it was then left to "age" during which time a slight increase in density was noted. The batch was stirred to make it homogenous and then allowed again to reach a settled condition, which turned out to be about a 50 percent solid content (Fig. 8(b)). Figure 9(a) displays a typical manufacturing cycle using the helium refrigeration method. Solid content of the newly produced SLH_2 is very high, due to having mechanical control over the size of the solid particles produced. After an aging period, this batch also was stirred and allowed to settle. It reached a 60 percent solids content (Fig. 9(b)). These results show proof that SLH_2 with a solid fraction considered necessary for future aerospace applications is no longer attainable just on a laboratory scale.

Programmatically speaking, the uniqueness of this facility will allow parametric exploration of the parameters affecting, and the resulting efficiencies, in the generic major production methods (evaporative cooling and helium refrigerated surface) now envisioned to manufacture SLH_2 in the quantities needed for a NASP. In addition, the facility provides the test bed needed for (1) selected flow component testing, (2) instrumentation testing, (3) exploration of selected safety issues in SLH_2 handling and storage, and (4) experimental validation of analytical study criteria from program-supporting grant efforts such as the Thermal Acoustic Oscillation work at the University of Colorado (see below).

4. NASA LEWIS RESEARCH CENTER PLUM BROOK STATION "K-SITE" FACILITY

Over the course of this last year NASA Lewis Center has brought its large scale SLH_2 test facility, K-Site, at the Plum Brook Station, to an operational readiness status. The immediate specific test objectives of this facility are to obtain; (1) parametric experimental data on the ramp pressurization and expulsion of SLH_2 tankage, (2) parametrically explore the process of recirculating back into the tank some of the propellant removed, (3) create slosh conditions within the test tank by physically imposing a shaking force, and (4) obtain empirical performance data on selected pieces of instrumentation usable in SLH_2 systems.

A diagram of this facility flow system is given as Fig. 10, and an overall photograph of the facility is seen in Fig. 11. The major subsystems of K-Site are (1) a SLH_2 generator tank (Fig. 12) identical in size and almost identical in appointments with the generator tank at the STF, (2) a 6000 cfm vacuum pumping system, (3) the test article containment vessel which is a 25-ft diameter hydrogen-spill-proof environmental chamber capable of hard vacuum level (Fig. 13), (4) the uninsulated test article, (5) and the LH_2 temperature bathed 3000 psig pressurant gas "conditioning tank". Two 13,000 gallon LH_2 storage and supply Dewars are also incorporated into K-Site. The 1300 gallon SLH_2 Generator Tank will produce 700 gallon batches of SLH_2 using the evaporative cooling method. All SLH_2 or LH_2 transfer lines are vacuum jacketed and of welded construction. The insulation system for the SLH_2 generator is the same as for the STF installation, the insulation for the test article is provided by the vacuum in the environmental chamber.

As with the generator tanks at the STF and at N.I.S.T, the internal volume of the K-Site generator can be visually monitored during operations. This provision, coupled with measurement of the density changes of the cryogenic within the tank, will determine when production of a batch of SLH_2 is complete, and its movement through the transfer line subsystem to the test article can be initiated. Once the transfer of the SLH_2 to the test tank in the chamber has been completed, experimentation in tank pressurization, expulsion, propellant recirculation, etc., can be performed. The hydrogen expelled from the test tank can be collected in either the SLH_2 generator or can be returned to one of the LH_2 storage Dewars for reprocessing/reuse. The site flow systems have just finished supporting a testing period for another NASA Lewis effort involving LH_2.

Programmatically speaking, this facility is unique in its capability to support parametric study of SLH_2 tankage pressurization, expulsion, and line flow investigations. A filled test article inside the chamber may remain static or it could be subjected to movement. Also, because the pressure level and the atmosphere composition within the chamber can be varied, K-Site lends itself readily to the thermal and hydraulic evaluation of prototype vehicle tankage under ground-hold, ascent, and reentry pressure profiles. This work can be done with good sized tankage without fear of a test article failure jeopardizing the facility (i.e., a 13-ft diameter LH_2 tank was used in the 1970's). This feature lends itself readily to the cryogenic testing of tanks which themselves are experimental in nature.

5. NASA LEWIS RESEARCH CENTER ANALYTICAL CODE EFFORT

In the analytical field, it should be recalled that prior to the onset of the NASP SLH_2 technology work at NASA Lewis there were no models existing which would allow prediction (a priori) of (1) pressurant gas requirements needed to pressure-expel SLH_2 from vehicle and/or storage tanks, nor (2) the pressure drop and solid-liquid percentage changes for SLH_2 flowing in piping systems. Codes to predict these things have been developed at NASA Lewis and await experimental data for their validation. The code which deals with pressurized expulsion of SLH_2 is named "EXPL"; the program dealing with line flow has been named "FLUSH" (Refs. [6] and [7]). These models are one-dimensional and are currently running on the VAX systems at NASA Lewis.

Predictive studies have been made using "EXPL" to quantify the increase in mass of autogeneous pressurant needed to expel SLH_2, as opposed to NBP LH_2, from a 5-ft diameter spherical test tank used in previous LH_2 experiments at K-Site. Figure 14 displays the result for the cases where the temperature of the incoming pressurant is 670 °R, and Fig. 15 for the cases using ambient temperature pressurant (540 °R). Predictions show an increase of between 35 and 41 percent when the warm pressurant is used, and increase of between 48 and 65 percent for the ambient pressurant gas cases. If pressurant gases even lower in temperature are employed, the difference in required mass of pressurant relative to NBP LH_2 expulsion will become even greater than what is shown here.

Over the last year (a) the "EXPL" code has been enlarged to accommodate pressurized expulsion using gaseous helium pressurant. In addition, a code named "SLURP" was developed to predict the one-dimensional thermodynamics and the mass transfer processes occurring in a SLH_2 tank as the tank is ramp-pressurized to its proposed steady-state operating level. The update on "EXPL" will be published this fall; the code entitled "SLURP" is available as Ref. [8].

There are envisioned selected aspects of the propellant tank modelling problem which might require the use of three-dimensional techniques. Over the last year NASA Lewis has put in place a grant effort to have researchers at Washington University (St. Louis, MO.) perform a survey of such codes (e.g., "FLOW-3D") and assess their usability when laid against a set of specific predictive needs. This will be finished this fiscal year, and will be followed with the construction and addition of specific subroutines to those programs which are selected as "most promising for our technological needs".

6. OTHER INTERAGENCY WORK - LOS ALAMOS NATIONAL LABORATORIES

The anticipated use of SLH_2 in any application requires both an understanding and an observance of any safety-related requirements existing beyond the ones observed for LH_2 alone. As far as NASA is concerned, as well as a considerable number of aerospace institutions, the safety requirements for LH_2 are well documented in NASA Technical Memorandum TM-X-52454 entitled "NASA Hydrogen Safety Manual." With regard to SLH_2 however, little formally published safety information was found to exist in the literature.

During the last year, personnel at the Los Alamos National Laboratories have compiled everything they were able to research on the safety issue for SLH_2. Their documentation of this information will be published this fall as a new chapter (Chapter 12) in the latest revision of "NASA Hydrogen Safety Manual." This additional chapter is envisioned as a "living" document, and subsequent additions to it are expected as more work is done with solid-liquid mixtures of hydrogen in any field of application. An additional publication by the same authors will be a report enumerating specific issues and problems in the field of SLH_2 safety which will need resolution through as-yet unscheduled analytical and/or experimental work. This compilation of issues and problems forms the basis for furthering the collection of data in this important discipline.

7. ACADEMIC INSTITUTIONS - UNIVERSITY OF COLORADO

Another major design issue in deep cryogenic systems are Thermally-driven Acoustic Oscillations (TAO's). These oscillations, if present, can "pump" a large amount of heat into a cryogenic liquid, not to mention any structural damage which they might do. Thermal oscillations are an ever-present possibility when working with SLH_2, and hence have to be explored and their determining characteristics mapped to insure their elimination in hardware designs.

A grant has been in place at the University of Colorado, (Colorado, U.S.A.) to (1) generalize the phenomena of TAO's in cryogenic equipment, (2) model the phenomenon of TAO's toward being able to predict frequency, amplitude, and the increased boiloff rate they could cause, and (3) compare theory and experiment to provide design parameters which may be employed to arrive at hardware designs which will suppress such oscillations in NBP LH_2 systems, in TP LH_2 systems, and in SLH_2 systems.

To date this effort has yielded a comprehensive literature search on TAO's (Ref. [9]) which has revealed a very promising method for a theoretical attack on the TAO problem. This theoretical model has been extended to describe the geometric "boundaries" which must be observed in hardware designs for LH_2 systems. Documentation of this work is presently in draft form. To follow in short order will be the criteria for TP LH_2 systems and the criteria for SLH_2 systems. As the amount of experimental work increases in the field of the NASP, as well as with hydrogen efforts in other endeavours, more and more data will become available for verifying these analyses for the various statepoints of cryogenic hydrogen.

8. CONCLUDING REMARKS

In conclusion then, what has been described is the layout of effort directed at the development of technology data which will allow safer, more predictable handling practices for cryogenic hydrogen in a slushed form. Technologically speaking, the effort is as complete as present resources permit, with concentration on code validations and empirical generation of other design data. The program involves a broad spectrum of participants with heavy emphasis on inclusion of, and building upon, the "corporate memory" of government, industry, and academia personnel who have worked in the field of slushed propellants. The data from this program will provide a sound basis upon which to not only commit to the use of SLH_2 as the fuel for the aerospace plane, but also to serve as a basis for subsequent efforts in both ground, airborne, and spaceborne vehicles and/or facilities.

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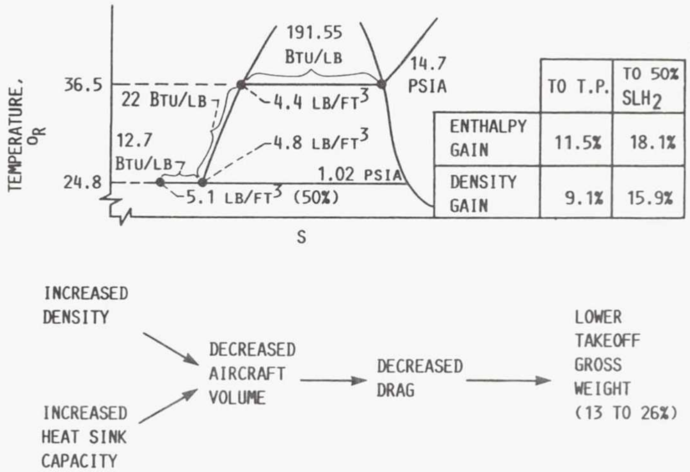


	TO T.P.	TO 50% SLH_2
ENTHALPY GAIN	11.5%	18.1%
DENSITY GAIN	9.1%	15.9%

FIGURE 1. - WHY SLUSH HYDROGEN (SLH_2) AS A FUEL?

A. FLIGHT SYSTEM TECHNOLOGY

B. PRODUCTION AND STORAGE TECHNOLOGY

C. PRODUCTION (COMMERCIAL)

D. STORAGE AND TRANSFER (COMMERCIAL)

E. PROTOTYPE FLIGHT TANK (APPLICATION)

F. SAFETY

FIGURE 2. - OVERALL PLAN ELEMENTS.

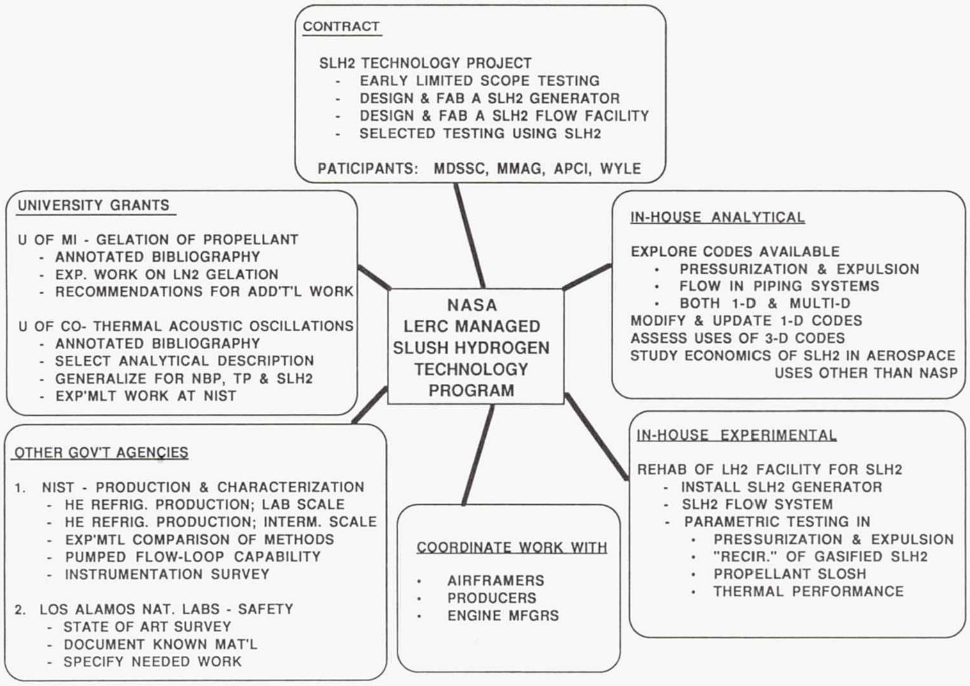


FIGURE 3. - SUMMARY OF SLH_2 TECHNOLOGY EFFORTS MANAGED BY LERC.

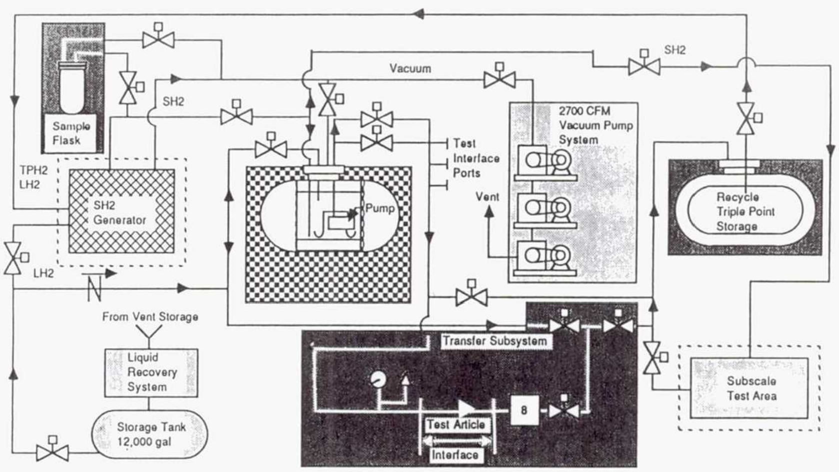


FIGURE 4. - SLUSH HYDROGEN TEST FACILITY, OVERALL SCHEMATIC.

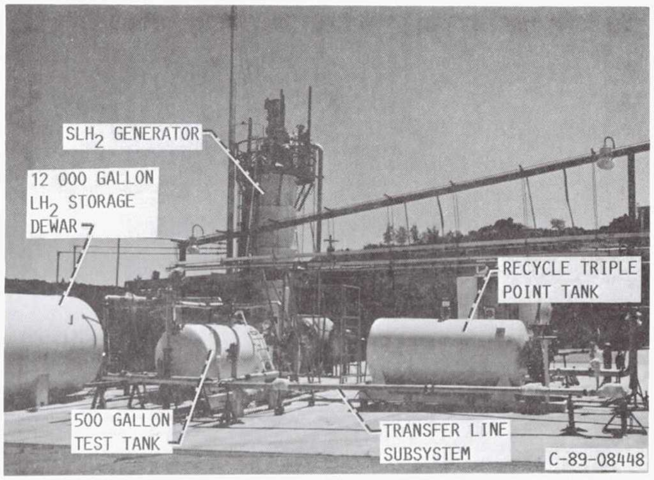


FIGURE 5. - OVERALL PHOTOGRAPH OF THE SLUSH TEST FACILITY AT MARTIN MARIETTA ASTRONAUTICS GROUP, DENVER CO.

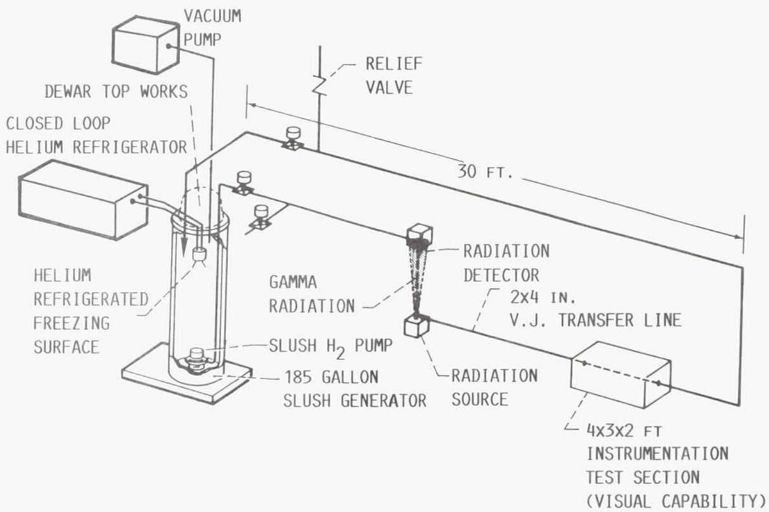


FIGURE 6. - N.I.S.T. SLUSH HYDROGEN FACILITY SCHEMATIC.

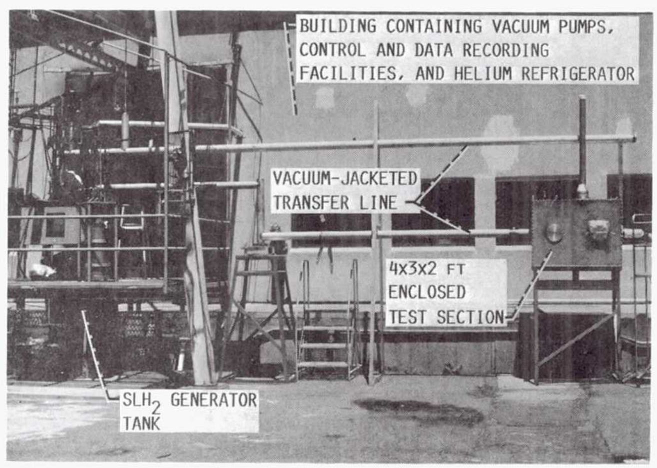
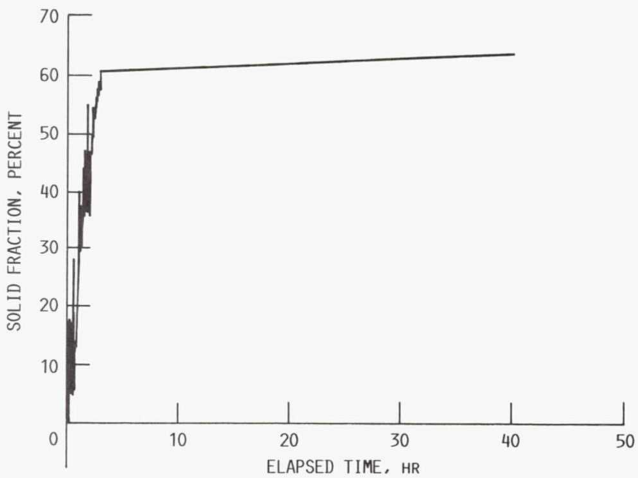
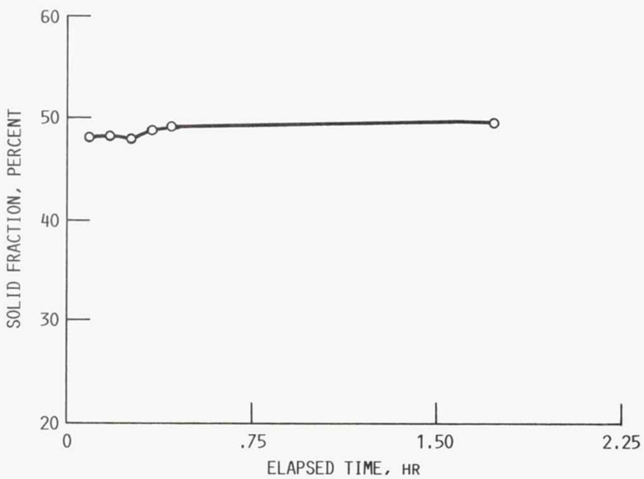


FIGURE 7. - OVERALL PHOTOGRAPH OF THE SLUSH HYDROGEN TEST FACILITY AT N.I.S.T.

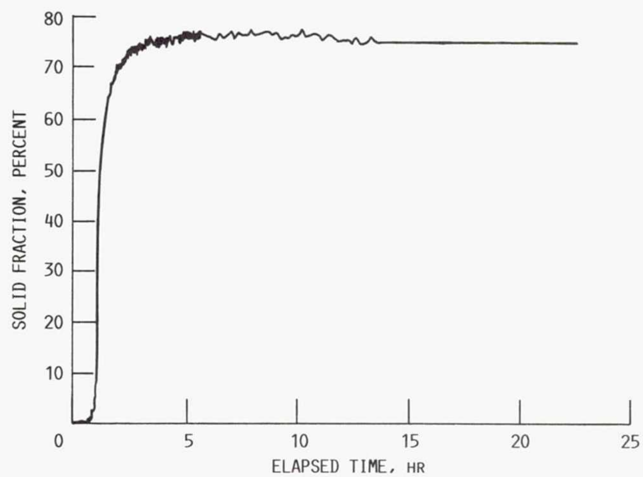


(a) SOLID FRACTION DURING PRODUCTION AND AGING OF SLUSH PRODUCED USING THE "EVAPORATIVE COOLING" METHOD.

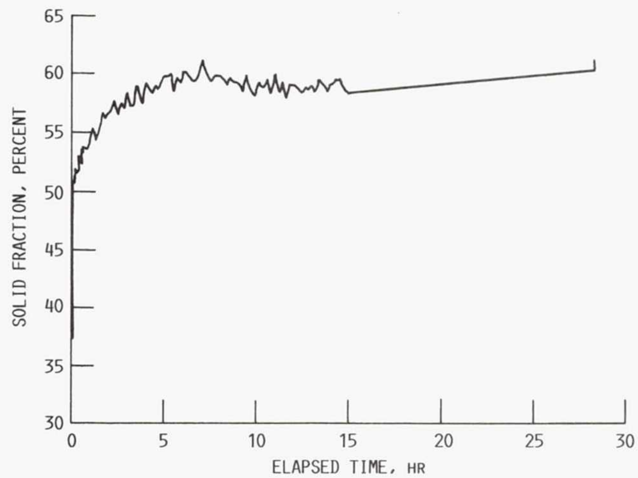


(b) SOLID FRACTION FOR AGED "EVAPORATIVELY COOLED" PRODUCED SLUSH AFTER IT WAS STIRRED. THE SLUSH WAS ABOUT 40 HOURS OLD WHEN IT WAS STIRRED.

FIGURE 8. - MANUFACTURING CYCLE FOR SLH_2 USING THE "EVAPORATIVE COOLING" METHOD.



(a) SETTLED SOLID FRACTION FOR AGING OF UNSTIRRED SLUSH PRODUCED USING THE "HELIUM REFRIGERATION" METHOD.



(b) SOLID FRACTION FOR AGED "HELIUM REFRIGERATION" PRODUCED SLUSH AFTER IT IS STIRRED. THE SLUSH WAS ABOUT 23 HOURS OLD WHEN IT WAS STIRRED.

FIGURE 9. - MANUFACTURING CYCLE FOR SLH_2 USING THE "HELIUM REFRIGERATION" METHOD.

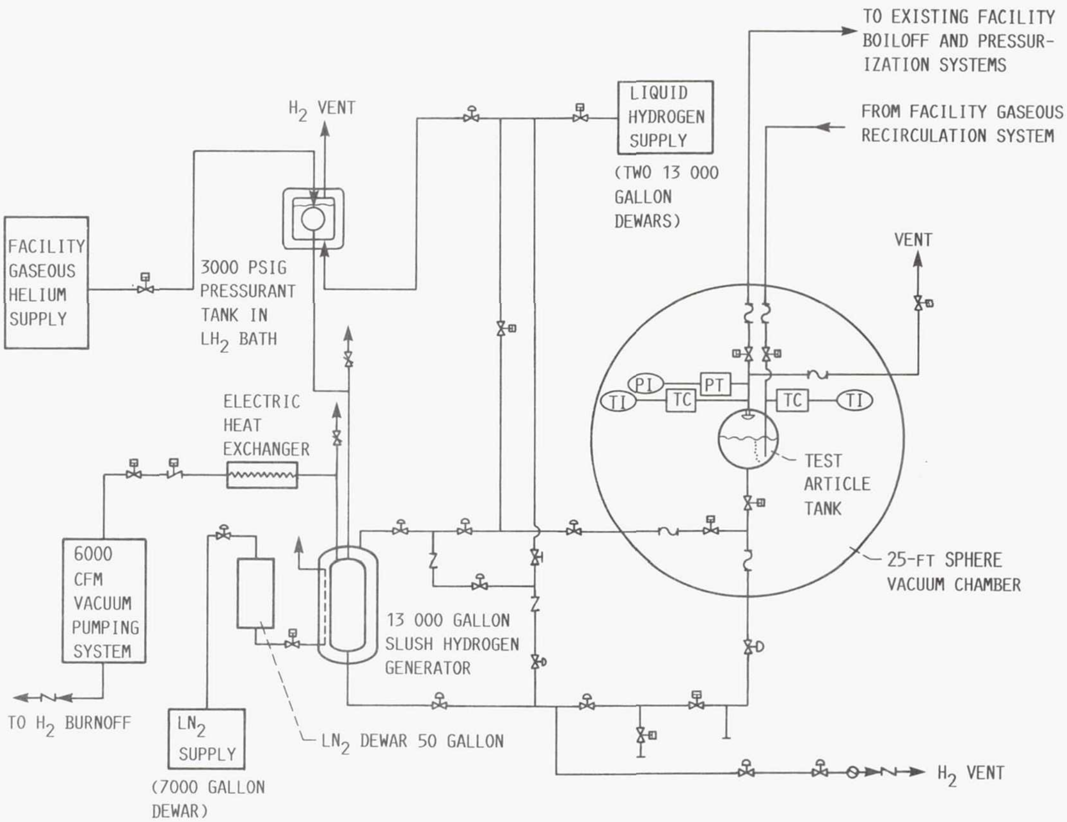


FIGURE 10. - NASA PLUM BROOK "K-SITE" FACILITY SCHEMATIC.

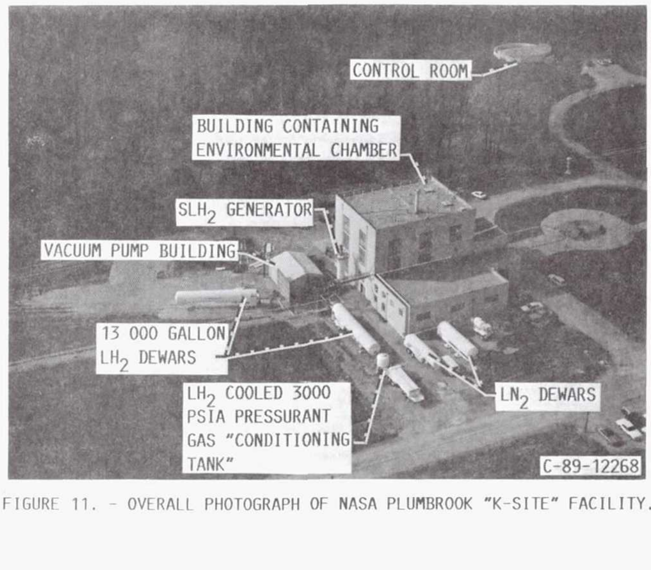


FIGURE 11. - OVERALL PHOTOGRAPH OF NASA PLUMBROOK "K-SITE" FACILITY.

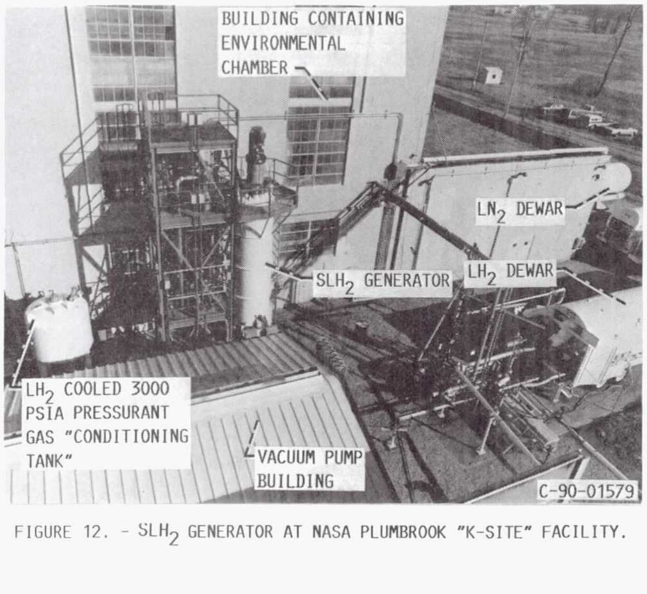


FIGURE 12. - SLH_2 GENERATOR AT NASA PLUMBROOK "K-SITE" FACILITY.

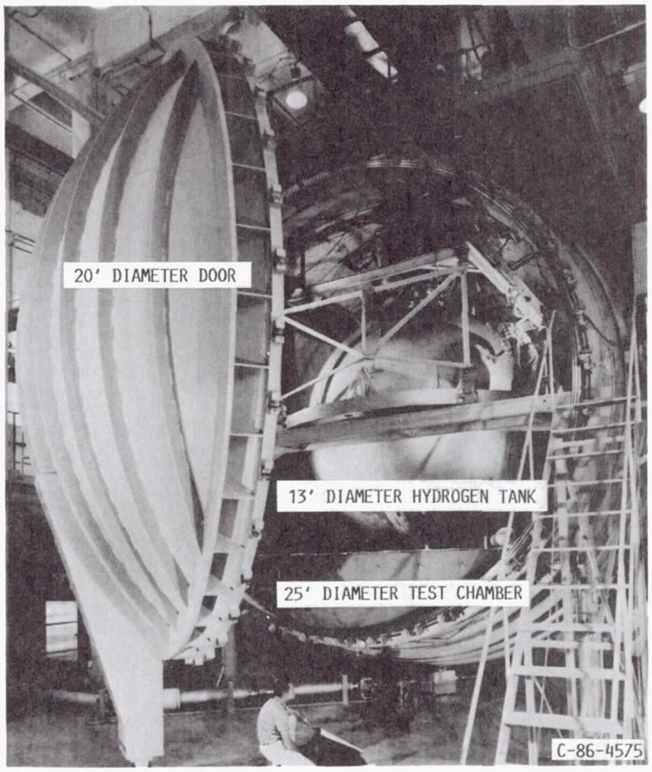


FIGURE 13. - CRYOGENIC PROPELLANT TANK LAB "K-SITE".

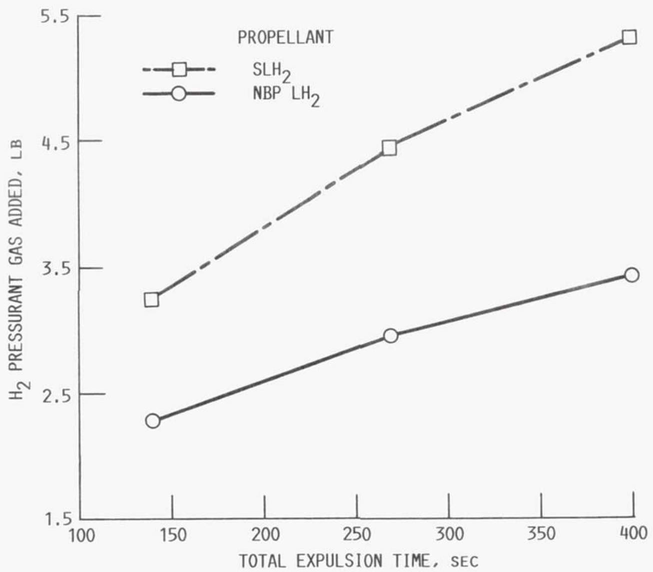


FIGURE 14. - COMPARISON OF GAS REQUIREMENTS FOR PRESSURIZED EXPULSION OF SLUSH HYDROGEN AND NORMAL BOILING POINT LIQUID HYDROGEN. (5 FOOT DIAMETER TANK; 50 PSIA; p-H_2; INLET GAS TEMPERATURE, 670 R).

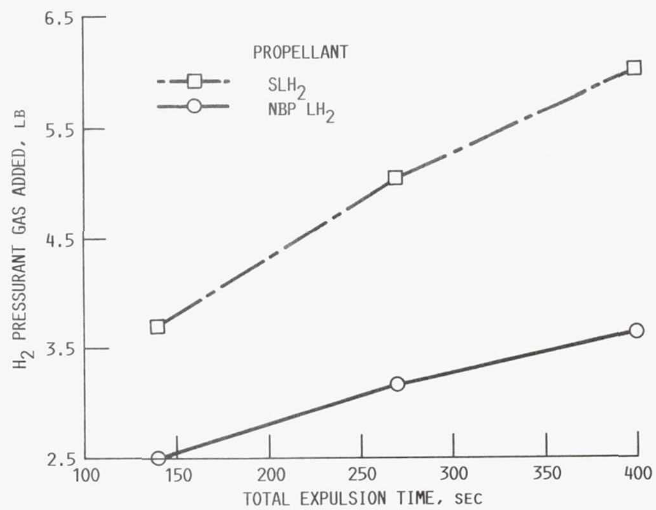


FIGURE 15. - COMPARISON OF GAS REQUIREMENTS FOR PRESSURIZED EXPULSION OF SLUSH HYDROGEN AND NORMAL BOILING POINT LIQUID HYDROGEN. (5 FT DIAMETER TANK; 50 PSIA; p-H_2; INLET GAS TEMPERATURE 540 R).

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16. Abstract

Among the Hydrogen Projects at the National Aeronautics and Space Administration's Lewis Research Center (NASA LeRC), Cleveland, Ohio, U.S.A., is the task of implementing and managing the Slush Hydrogen (SLH_2) Technology Program for the United States' National AeroSpace Plane Joint Program Office (NASP JPO). The objectives of this NASA LeRC program are (1) to provide verified numerical models of fluid production, storage, transfer, and feed systems and (2) to provide verified design criteria for other engineered aspects of SLH_2 systems germane to a NASP. The pursuit of these objectives is multidimensional, covers a range of problem areas, works these to different levels of depth, and takes advantage of the resources available in private industry, academia, and the U.S. Government. This paper is a summary of the NASA LeRC overall SLH_2 program plan, its implementation, the present level of effort in each of the program areas, some of the results already in hand, and the prognosis for the effort in the immediate future.

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