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Slush Hydrogen (SLH2) Technology Development for Application to the National Aerospace Plane (NASP)

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SLUSH HYDROGEN (SLH2) TECHNOLOGY DEVELOPMENT FOR APPLICATION TO THE NATIONAL AEROSPACE PLANE (NASP)

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ABSTRACT

The NASP program is giving us the opportunity to reach new unique answers in a number of engineering categories. The answers are considered "enhancing technology" or "enabling technology". Airframe materials and densified propellants are examples of "enabling" technology.

The National Aeronautics and Space Administration's Lewis Research Center has the task of providing the technology data which will be used as the basis to decide if slush hydrogen (SLH2) will be the fuel of choice for the NASP. The objectives of this NASA Lewis program are (1) to provide, where possible, verified numerical models of fluid production, storage, transfer, and feed systems, and (2) to provide verified design criteria for other engineered aspects of SLH2 systems germane to a NASP. This program is a multiyear multimillion dollar effort. The present pursuit of the above listed 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 will be a summary of the NASA Lewis overall program plan. The initial implementation of the plan will be unfolded and the present level of efforts in each of the resource areas will be discussed. Results already in hand will be pointed out. The paper will conclude with a description of additionally planned near-term experimental and analytical work.

INTRODUCTION

The NASA Lewis Research has the task of providing the technology data which will be used as the basis to decide if slush hydrogen (SLH2) will be the fuel of choice for the NASP. The reason for consideration of

SLH2, 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 "neat" liquid, which is ordinary normal boiling point (NBP) hydrogen.

Figure 1 displays the statepoints of NBP LH_2 and of 50 percent solids content SLH2. Relative to the heat of vaporization at 1 atm 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 going 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 achieved by going all the way to the 50 percent quality statepoint in the solid-liquid region. The use of dense SLH2 rather than neat liquid as the cryogenic working fluid will yield reduced vehicle size and a correspondingly lighter weight vehicle. The benefits are compounded by a factor of 2 to 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).

The desired effective use of SLH2 as both a coolant and propellant results in the need for advanced production, storage, and feed system technology. From the NASP standpoint this work with SLH2 is presently considered an "enabling technology." Were only the strategic planning arena for other aerospace applications considered, the work is still an "enhancing technology."

This particular SLH2 technology program had the following generalized overall objectives:

(1) To provide a data base for a decision to use a SLH2 or a LH_2 storage and feed system in NASP and in future NASP-derived vehicles,

(2) To provide verified numerical models of fluid storage, transfer, and feed systems, and

(3) To provide verified design criteria for SLH2 storage and feed systems.

The first objective is concerned with the development of the technology data that is needed in order to enable a decision regarding which statepoint of the fuel would best suit specific needs. The computational models of the second objective are needed to describe the SLH2 behavior under the conditions of storage, transfer, and use. Also, there are design criteria, of the third objective, which will be needed to be verified by empirical work.

The approach is to conduct analytical studies which will help to define the technology problems. Concurrently the experimental verification work required for the models is being conducted. Finally, the tools and data generated will be used to investigate the application employing "Proof-of-Concept" (POC) hardware.

In planning the overall program a six element partition was postulated. It is recognized that this partition is somewhat subjective, however, it was a good starting point. The six elements are listed in

Fig. 2. The main steps of solution are considered to be (a) analysis, (b) technology work, and (c) experimentation for verification. Analysis work is part of the first four elements of the plan; technology work will be accomplished as part of the first two elements. Experimental work is laced throughout all six elements. In the fourth and fifth items the experimental work is directed at verification of the anticipated designs. Lastly, safety issues will be treated within each element, but an overall "across the board" safety effort is also underway. These plan elements embody activity in the theatres of operation of (1) technology, (2) proto-production, (3) proto-flight, (4) full scale production, and (5) full scale flight.

Each of the plan elements listed in Fig. 2 were further partitioned into specific items which fell into either an "experiment," an "analysis," or a "study" category. A complete documentation of this plan can be found in Ref. 1.

The Plan being discussed is being implemented in a "pieces-parts" fashion, 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 the 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. A further partitioning of the work efforts is anticipated in the next fiscal year. For the present, however, this paper will be concerned only with discussion of the efforts shown in the figure.

CONTRACT WORK...McDONNELL DOUGLAS SPACE SYSTEMS COMPANY

In the Contract Area one major effort, that with McDonnell Douglas Space Systems Company, will be highlighted. The immediate specific objectives of this effort include the design, the fabrication, and the exercise of an experimental slush hydrogen test facility (STF) to obtain; (a) data on methods and rates of SLH2 formation using the evaporative cooling method, (b) definition of some selected flow characteristics of SLH2, (c) investigatory data on pressurization of SLH2 tankage, and (d) exploratory data and performance data on selected pieces of instrumentation usable in SLH2 systems.

During the design and fabrication of some of the major pieces of hardware which will ultimately comprise the STF, several already existing container vessels were experimentally exercised with SLH2.

One such vessel was the glass Dewar, of about 76 l (20 gal) capacity, shown in Fig. 4. It was used to explore development of a repeatable procedure for producing SLH2 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. Several of the qualitative results from this work are as follows:

(a) Agitation of the SLH2 is needed during production or large agglomerations of solids result

(b) Excessive agitation causes additional exposure of solid to the ullage volume and also causes increased surface sloshing about the penetrations

(c) Higher quality SLH2 was produced for the tests having the shorter freeze-thaw pressure cycle histories

(d) The evacuation pumping rate value listed in the NBS literature appears to be substantiated by the results of these tests.

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.[2]

A second subset of equipment involved a vacuum jacketed Dewar, of about 1893 l (500 gal) capacity, shown in Fig. 5. It was used to conduct some pre-expulsion tank pressurizations, and some propellant expulsion activity, with different pressurant gases. Initial tests were made using only cold GHe, subsequent to that were tests using only warm GH2, and finally some tests using GHe to bring the tank ullage up to the desired pressure level followed by an autogenous gas 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. Several of the qualitative results from this work are as follows:

(a) Pressurization of TP LH_2 with cold GHe: readily accomplished, very little ullage pressure collapse at the initiation of outflow.

(b) Pressurization of SLH2 with cold GHe: took considerably longer (the cooling of the GHe by the melting SLH2 is suspect), no ullage pressure collapse at the initiation of outflow.

(c) Pressurization of TP LH2 and SLH2 with warm GH2: very easily accomplished, significant ullage pressure collapse at the initiation of outflow.

(d) Pressurization of TP and SLH2 initially with GHe, followed by use of GH_2: Essentially no collapse of the ullage pressure (it is suspected that the blanketing effect from the GHe might be reducing any condensation of the GH_2 pressurant).

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[3]

Both subsystems, namely the 76 l (20 gal) glass Dewar and the 1893 l (500 gal) tank, are presently being plumbed into the STF, which will be located in the Engineering Propulsion Laboratory at Martin Marietta outside of Denver, Colorado. The STF, when finished, will also include a 227 kg (500 lbs) per batch SLH2 production vessel for supplying the slushed product needed for further pressurization testing, flow line work, and instrumentation work. Another paper at this Conference[4] further details both the STF and Pre-STF test results.

CONTRACT WORK...AIR PRODUCTS AND CHEMICALS INC.

A major subcontract effort, the end product of which meshes with the STF and also with the yet-to-be discussed in-house NASA Lewis effort, is the work which Air Products and Chemicals Inc. (APCI) is accomplishing. This subcontract, for the manufacturing of a SLH2 generator tank, deals with the "next step in the evolution of SLH2 production tankage."

Figure 6 displays the first such unit which is being installed at the STF. It is a vertical, double walled cylinder, having in the annulus MLI as well as a LN2 cooled shield. It has a volume of 4921 l (1300 gal) and can produce a 227 kg (500 lb) batch of SLH2 from an initial charge of 286 kg (630 lbs) of propellant. The complete production cycle design time is about 8 hr. A second unit is being installed at the NASA Lewis Research Center Plum Brook Station Facility.

INTERAGENCY WORK...NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY

The technique of production for the manufacture of large quantities of SLH2 is still a matter of significant concern. The quantities spoken of here are in the category involving hundreds of thousands of pounds. To design large scale systems to produce and utilize SLH2 for a single stage to orbit (SSTO) application requires process data which is relatively complete. From an engineering standpoint there are only a few methods for which sufficient data exists to even begin a study of manufacturing SLH2 in "research-need quantities," let alone its manufacture in quantities such as mentioned above. These methods are (a) "Evaporative Cooling" (i.e., known in the industry as the "Freeze-Thaw" method), (b) LHe refrigeration (colloquially referred to as the "Auger" method because of the need of mechanically removing the solid hydrogen from a refrigerated surface on which it forms), and (c) magnetic refrigeration. The Evaporative Cooling method is characterized fairly well. The refrigeration process needs an experimental parametric study to be accomplished to provide a sound engineering data base from which to scale larger units. The magnetic refrigeration method is more deeply immersed in a preliminary design phase so it is not presently part of any study devoted to methods of large quantity production, however this method might yet prove useful in the SLH2 upgrading process for an already-filled vehicle or storage tank. This method will not be carried further in this discussion.

The evaporative cooling technique has been fairly well defined. The NBS (now NIST) did the bulk of its experimental parametric exploration back in the late 60's and early 70's. Only a limited amount of work, however, has been done with the LHe refrigeration method, and no head-to-head comparison of the methods has been done in the same test installation. Hence, questions such as the size and shape of particles produced, the settled SLH2 density, SLH2 production capacity versus auger torque requirements, production capacity versus auger size, effect of clearance between the scraped surface and the moving blade, effect of auger rotational speed, and the effect of the quality of the scraped surface on production are all parameters which need further definition.

The NIST has a two pronged SLH2 effort underway, one major thrust of which deals with production of SLH2. Two auger test facilities have been constructed at the NIST. The first, a small glass apparatus of about 30.3 l (8 gal) capacity, is where the metrology (i.e., size and weight characteristics) of the solid particles produced, as well as some auger operating characteristics, were investigated. Conclusions reached from this small scale work can be stated as follows:

(a) The small auger produced SLH2 that stirred easily and appeared to moved easily in the Dewar when aged. This characteristic is the same as was observed with the product produced via the evaporative cooling method.

(b) Fresh SLH2 particle sizes produced by the small auger depended on the clearance between the auger and the scraped wall. The particles were smaller for lower clearances. Upon aging the particle sizes generally seemed to increase.

(c) Based on particle size measurements, pressure drops for SLH2 flowing in pipes, settled SLH2 densities in storage vessels, stirring energies, and other handling characteristics of auger-produced SLH2 are expected to be similar to those measured for SLH2 produced by evaporative cooling.

(d) An operating submerged auger does not disturb a stratified liquid surface layer, This allows SLH2 to be produced with higher than atmospheric pressure in the SLH2 generator vessel.

(e) Energies to scrape the SLH2 from the refrigerated surface of the auger assembly approached 15 percent of the refrigeration supplied to the auger. In future assemblies this can be reduced by a factor of 10.

(f) In a test unrelated to the small auger performance, a sample of SLH2 was intentionally contaminated with nitrogen. The frozen particles of nitrogen were so small that they settled slower than the SLH2 particles. Hence, if air contamination acts in a similar fashion, the contamination will be distributed throughout the settled SLH2 and it will tend to accompany the SLH2 as it is transferred.

This small-Dewar effort has been concluded and the above results, among others, will be documented in the soon to be released Reference 5.

In the meantime the NIST has continued assembly of a larger SLH2 facility, of about 760 l (200 gal) size, which is just now coming into operation, and will be used to more accurately confirm the above preliminary results as well as to obtain data which will define the effect of size-scaling of auger units. The auger assembly to be used in this larger NIST facility will be presented as Paper DC-06[6] at this conference. This larger facility can also make SLH2 via the evaporative cooling method and hence will allow the first head-to-head comparison of the evaporative cooling and the refrigeration methods of SLH2 production. Also this large facility will incorporate a SLH2 pump flow loop to explore critical pump parameters such as speed, input power, head rise, and density change across the pump. The flow loop can also be used to determine critical flow parameters (e.g., critical bulk velocity needed to keep solids in suspension).

The second major thrust of work being done by NIST deals with instrumentation. In this subject area is contained a basic need of any effort, whether it be for technology work alone, directed-development, or an immediate application. The NIST was given the job of surveying the instrumentation which already has been used in SLH2 systems as well as any other cryogenic-type transducers which have come onto the market in the last 20 years. The survey concentrated on techniques and transducers for the measurement of temperature, pressure, density, liquid level, tank gauging, and mass flow. This group of instruments was then screened to determine which units show promise, and what their state of readiness is for use in SLH2 work. The information has been collected, analyzed, and has been published as Ref. 7. The continuation of instrumentation work at NIST will be reflected in the actual testing of a number of transducers within the 760 l (200 gal) tank itself as well as in a specially designed test section in the facility flow loop. Selected pressure, temperature, density, and flow instruments will be evaluated using SLH2.

INTERAGENCY WORK...LOS ALAMOS NATIONAL LABORATORIES

The anticipated use of SLH2 in a vehicle application, or in basic technology development for that matter, requires both an understanding and an observance of any safety-related requirements existing beyond those observed for LH2 alone. As far as the NASA is concerned, as well as a considerable number of aerospace institutions, the safety requirements for LH2 are well documented in Ref. 8. To begin the furtherance of work in this discipline for the hydrogen in slushed form, an interagency agreement was set up in October of 1988 between NASA Lewis and the Los Alamos National Laboratories. This effort has a threefold objective.

The first level of effort dealt with a literature search for references on SLH2 and also with a direct interfacing with the Producers and major Aerospace Contractors. This latter activity had the purpose of uncovering any unpublished information as well as to solicit parochial problems as seen by the institutions directly involved with major aspects of the NASP program. Following this first objective was a period of identification of topics, as well as definition of specific line items within those topics, which need analytical or experimental efforts for investigation, definition, and/or resolution. Contamination of the SLH2 looks to be a possible major problem area. Specifically, the degree of contamination measureable, and how that translates into a safety concern, is surfacing as a major issue. The third objective, which presently is underway, is to complete several chapters on SLH2 safety which could be directly added to the NASA LH_2 safety manual.[8] It is envisioned that these chapters would also include notes relative to specific items in all preceding chapters which would be affected by changing the statepoint of the propellant from LH_2 to SLH2.

This 1-year effort is now nearing completion. A literature search has been done and is being compiled to show major findings. An outline for the chapter additions to NASA TMX-52454 exists and has been reviewed with the major hydrogen Producers and Aerospace Companies in the NASP arena. The same exposure and review has just been completed for jobs which still need to be dealt with in the investigation, definition, and/or resolution of known safety-type questions. The prognosis for this specific line item listing is the contracting of small experimental and/or analytical jobs specified in this study.

ACADEMIC INSTITUTIONS...UNIVERSITY OF MICHIGAN

The controlling of a liquid or quasi-liquid propellant in the tank of a moving vehicle will be a qualification laid on the design of any NASP Vehicle Contractor. One possible way to attain better control of the propellant is by densifying it into a "gel" (i.e., a coherent system composed of a dispersion medium and a disperse part, the latter having particles of colloidal dimensions, with the particles of the disperse part at a standstill").

The University of Michigan has been working at assessing the state of knowledge and the engineering aspects of "gelled" and "gelled slush" cryogenic propellants. Their effort included (a) searching the literature for the materials related to production, properties (equilibrium and transport), storage, transport, heat transfer, and chemical reaction of such propellants, (b) making an engineering analysis of the various aspects associated with the usage of these propellants and arrive at (c) a critical evaluation of the status of knowledge and (d) recommend the areas where further efforts are needed. The results of the first 1-year effort is the report of Ref. 9.

One major revelation of the review was that the production, hydrodynamics, and the heat transfer aspects of gelled hydrogen are not at all well understood. This second year of effort by U. Of M. staffers is well underway to parametrically investigate the gel production technique which employs a submerged gellant-gas jet in a host liquid. Liquid nitrogen is being used to simulate the propellant, and butane gas is the gellant. This work is being paralleled with analyses in order to provide a tool which will serve to generalize the results. Flow testing with the formed gel is being done and pressure drop values are being measured in order to arrive at apparent viscosity numbers. The flow through constrictions, and the degradations such as nonuniformity in concentration, mass deposits, etc., are also being examined. In the heat transfer arena the boiloff rate of gels, relative to neat liquid, is being compared. One of the references in the literature states that "gelling showed reduced evaporation rate (i.e., 25 to 50 percent), resistance to vibratory acceleration, and shock acceleration".[10] The latter two are desirable, however U. of M. investigators are not finding the reduction in boiloff, at least not with the LN_2 test work referred tp above. Reference 11 shows that at least for LN_2 gelled with butane just the opposite is true, and is of considerable consequence in magnitude.

Two points are evident here: (a) experimental work done for a very pointed objective, say, 2 decades ago should be revisited, and (b) the product formed should be investigated for its characteristics over a range of input conditions (i.e., sloshing motion plus heat transfer). In conclusion then it can be said, that if the experimental result now inhand holds up under further analysis, then the gelling of hydrogen propellant does not seem to be of value for the NASP application.

ACADEMIC INSTITUTIONS...UNIVERSITY OF COLORADO

Another major problem in deep cryogenic systems is that of are thermally driven acoustic oscillations (i.e., TAO's). In any arrangement where a tube penetrates a cryogenic storage vessel, or a cryogenic line for that matter, the tube can become filled with vapor due to normal boiloff of the cold liquid. A pressure surge can be initiated by expansion of the fluid as it is heated at its closed end. Since these tubes are generally used for filling the tank, venting, pressure relief, instrumentation taps, etc., their closed end is either close to or at ambient temperature. This surge, in turn, forces vapor from the tube at the open end into the storage vessel. Cool vapor is then withdrawn from the cryogenic tank or line back into the tube to replace the ejected mass, and a cyclic oscillatory process begins. These oscillations, if present, can "pump" a large amount of heat into a cryogenic liquid, not to mention any structural damage of the line or tank which they might do. These type oscillations are readily experienced by cryogenic experimentalists, and especially when using LHe. Thermal oscillations are an ever-present possibility when working with SLH2, and hence have to be explored and their determining characteristics mapped to insure their elimination in future applications.

A grant has been put in place at the University of Colorado having the following objectives: (a) generalize the phenomena of TAO's in cryogenic equipment, (b) provide conceptual understanding of TAO's which may be at least empirically applied to deep cryogenic systems thereby reducing heat leak and eliminating potential damage due to oscillations, (c) model the phenomenon of TAO's toward being able to predict frequency, amplitude, and boiloff rate due to them, (d) compare theory and experiment to provide system design parameters which may be used to suppress oscillations, and (e) use LHe to experimentally investigate, and provide a sound theoretical model for transferring LHe experimental results to SLH2.

To date this effort has yielded a comprehensive literature search which has revealed a very successful theoretical attack on the TAO problem upon which this grant effort can build. Experimental work with LHe will be planned and conducted at the U. of CO. Work with SLH2 will be incorporated into the ongoing experimental effort at NIST.

NASA LEWIS RESEARCH CENTER

The NASA Lewis has been given the management and leadership roles in the NASP Technology Maturation Program dealing with SLH2 Technology. In parallel with all the efforts mentioned above, work is being carried in both the analytical and the experimental arenas within the NASA Lewis lab itself.

In the analytical field there were no models existing which would allow prediction (a priori) of (a) pressurant gas requirements needed to pressure-expel SLH2 from vehicle and/or storage tanks, nor (b) pressure drop and solid-liquid percentage changes for SLH2 flowing in piping systems. These have both been developed at NASA Lewis and await experimental data for their validation. The model which deals with pressurized expulsion of SLH2 is named "EXPL;" the program dealing with line flow has been named "FLUSH."

The model dealing with the pressurized expulsion is based on a computer code developed in the 70's at NASA Lewis for the expulsion of neat liquid hydrogen. The original program calculates ullage gas and tank wall temperature distributions as well as pressurant gas requirements. Modifications made to account for the SLH2 case are (1) the inclusion of the thermodynamic and transport properties of solid-liquid mixtures of hydrogen, (2) energy transfer to the propellant and the resulting solid fraction change, and (3) a mass transfer approximation at the interface between the ullage and the propellant. A comparison of EXPL analytical results with LH_2 expulsion test data has been made using experimental data published in Ref. 12 to test the accuracy of the analytical model. This comparison work indicates that the code provides accurate predictions of pressurant gas requirements, wall and gas temperature profiles, and the energy gains occurring during an expulsion. An example of temperature distribution results is shown in Fig. 7. These agreements, as well as a description of the computer code, is available as Ref. 13 soon to be published as a NASP Report. Reference 13 deals with the case using GH2 as a pressurant. Additional revisions to the code are currently being made to permit the use of GHe as the pressurant.

The second major modeling effort was developed in order to be able to perform calculations for in-line transfer of solid-liquid mixtures of hydrogen. The "FLUSH" code calculates pressure drop and solid fraction loss for the flow of SLH2 through pipe systems. The model solves the steady state one-dimensional equation of energy to obtain an estimate of the SLH2 solid fraction decrease. This report is available as Ref. 14.

The other major part of the NASA Lewis SLH2 technology work lies in the experimental arena. A twofold objective exists here, the first being to provide data to parametrically verify the analytical codes and, secondly, to provide empirical answers for those technology problems which presently escape analytical modeling (e.g., pressurant requirements under slosh conditions). The approach to meeting these program objectives is to reactivate and modify a large 7.6 m (25 ft) diameter spherical vacuum chamber facility at the NASA Lewis PlumBrook Station. This facility was used in the 60's and 70's to evaluate flow dynamics and thermal protection problems for neat liquid hydrogen tankage subsystems. This facility, closed down in 1974, has been subjected to a reactivation effort over the last year and is ready for test work. The heart of the facility, the 7.6 m (25 ft) spherical chamber, (Fig. 8), will be used to house test articles under study. A SLH2 generator subsystem similar to the one being built at MMAG, has been added to the facility. Figure 9 shows the SLH2 generator tank.

The imminent test effort will be directed at obtaining pressurization and expulsion data using initially a 1.52 m (5 ft) diameter spherical tank which has been carefully instrumented to provide the temperature measurements that are needed for verification of the subdivisions of the analytical code. One characteristic of the facility is that test tankage can be shaken while being emptied. Figure 10 shows the 1.52 m (5 ft) diameter test tank, a view of the temperature transducer rake which mounts inside the tank, and the shaker arm which pierces the environmental chamber wall in order to impart motion to the test article.

The test program will obtain experimental data for tank expulsion over a range of tank pressure levels, inlet pressurant gas temperature values, and expulsion rates, for both static tank and slosh conditions. Figure 11 shows a simplified version of the mass and energy balances that the data reduction program will generate with the data which will be collected.

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 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 SLH2 as the fuel for the Aero-Space plane, but also to serve as an excellent basis from which to commit to subsequent development efforts in both ground, airborne, and spaceborne vehicles and/or facilities.

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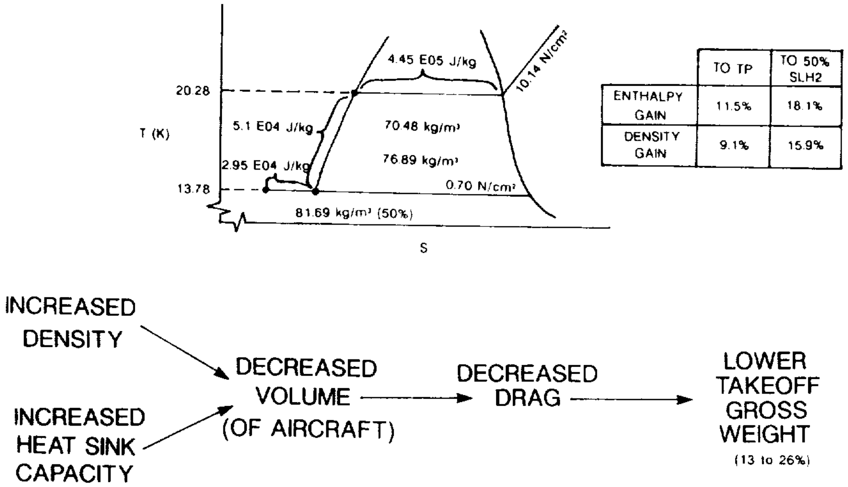


	TO TP	TO 50% SLH2
ENTHALPY GAIN	11.5%	18.1%
DENSITY GAIN	9.1%	15.9%

FIGURE 1. - WHY SLUSH HYDROGEN AS A FUEL?

OVERALL PLAN ELEMENTS

A. FLIGHT SYSTEM TECHNOLOGY

B. PRODUCTION AND STORAGE TECHNOLOGY

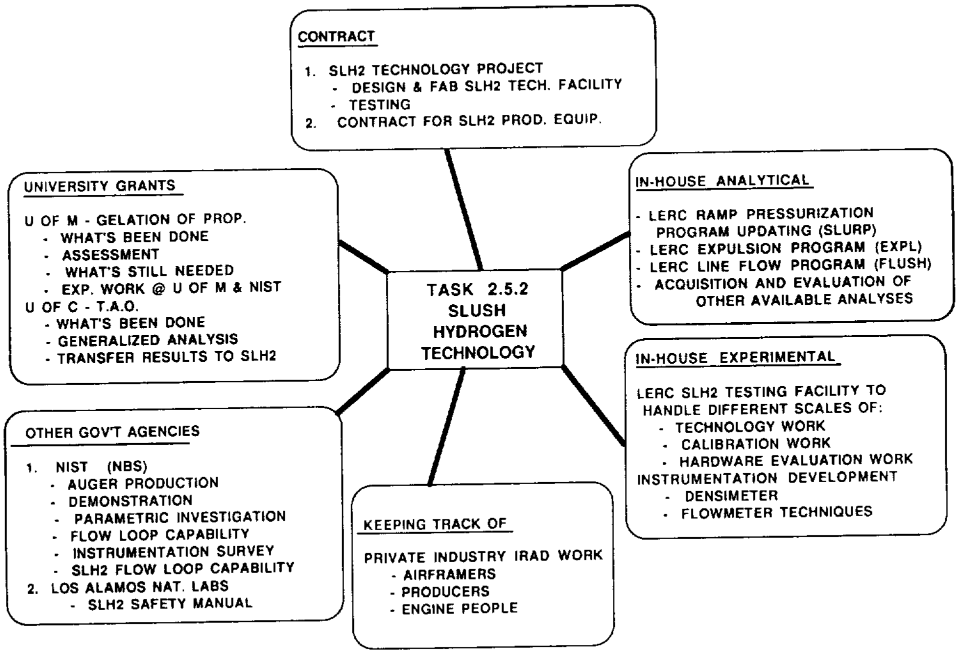
C. PRODUCTION (COMMERCIAL)

D. STORAGE AND TRANSFER (COMMERCIAL)

E. PROTOTYPE FLIGHT TANK (APPLICATION)

F. SAFETY

FIGURE 2. - SLUSH HYDROGEN TECHNOLOGY.



TASK 2.5.2 SLUSH HYDROGEN TECHNOLOGY

CONTRACT

1. SLH2 TECHNOLOGY PROJECT
   - DESIGN & FAB SLH2 TECH. FACILITY
   - TESTING
2. CONTRACT FOR SLH2 PROD. EQUIP.

UNIVERSITY GRANTS

U OF M - GELATION OF PROP.
- WHAT'S BEEN DONE
- ASSESSMENT
- WHAT'S STILL NEEDED
- EXP. WORK @ U OF M & NIST

U OF C - T.A.O.
- WHAT'S BEEN DONE
- GENERALIZED ANALYSIS
- TRANSFER RESULTS TO SLH2

IN-HOUSE ANALYTICAL

- LERC RAMP PRESSURIZATION PROGRAM UPDATING (SLURP)
- LERC EXPULSION PROGRAM (EXPL)
- LERC LINE FLOW PROGRAM (FLUSH)
- ACQUISITION AND EVALUATION OF OTHER AVAILABLE ANALYSES

IN-HOUSE EXPERIMENTAL

LERC SLH2 TESTING FACILITY TO HANDLE DIFFERENT SCALES OF:
- TECHNOLOGY WORK
- CALIBRATION WORK
- HARDWARE EVALUATION WORK

INSTRUMENTATION DEVELOPMENT
- DENSIMETER
- FLOWMETER TECHNIQUES

OTHER GOV'T AGENCIES

1. NIST (NBS)
   - AUGER PRODUCTION
   - DEMONSTRATION
   - PARAMETRIC INVESTIGATION
   - FLOW LOOP CAPABILITY
   - INSTRUMENTATION SURVEY
   - SLH2 FLOW LOOP CAPABILITY
2. LOS ALAMOS NAT. LABS
   - SLH2 SAFETY MANUAL

KEEPING TRACK OF

PRIVATE INDUSTRY IRAD WORK
- AIRFRAMERS
- PRODUCERS
- ENGINE PEOPLE

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

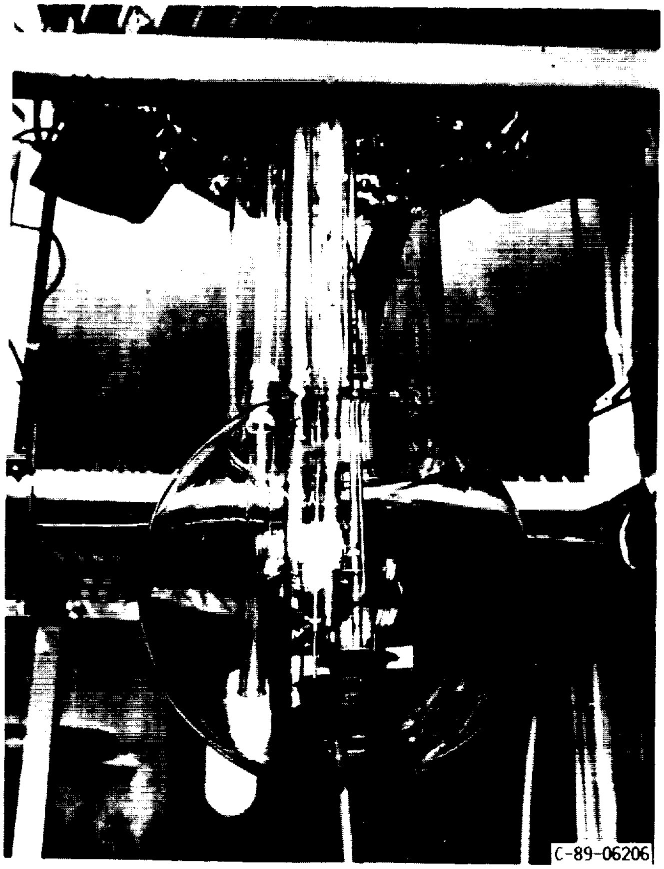


FIGURE 4. - 76 LITER GLASS DEWAR TEST VESSEL

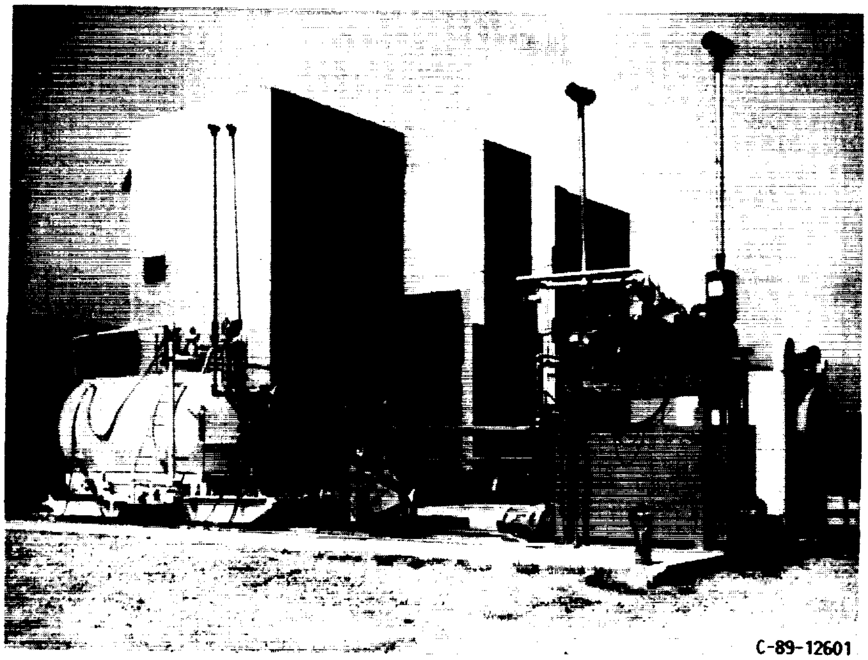


FIGURE 5. - 1893 LITER SLUSH HYDROGEN TEST VESSEL.

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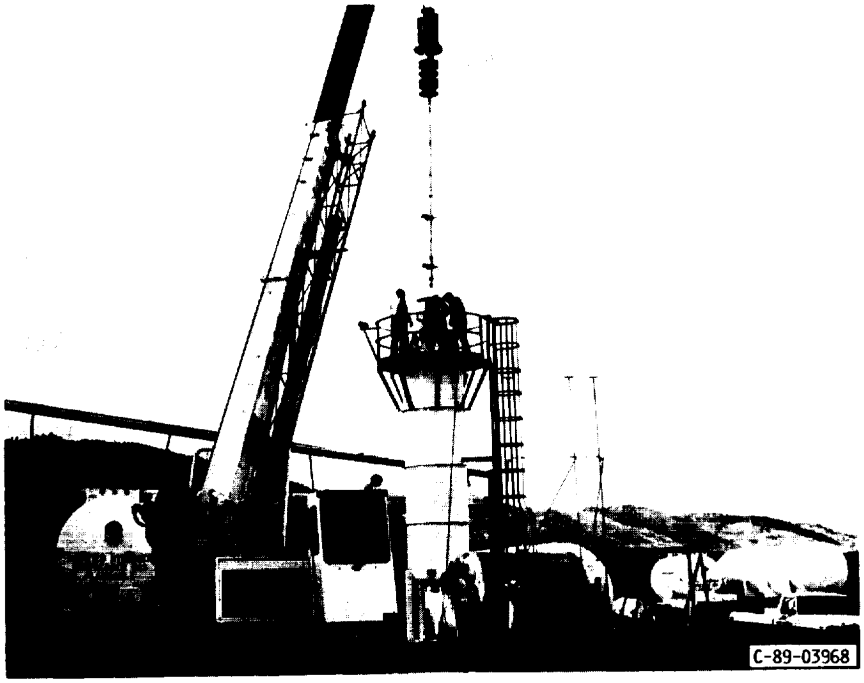

FIGURE 6. - SLUSH GENERATOR TANK LOCATED IN DENVER.

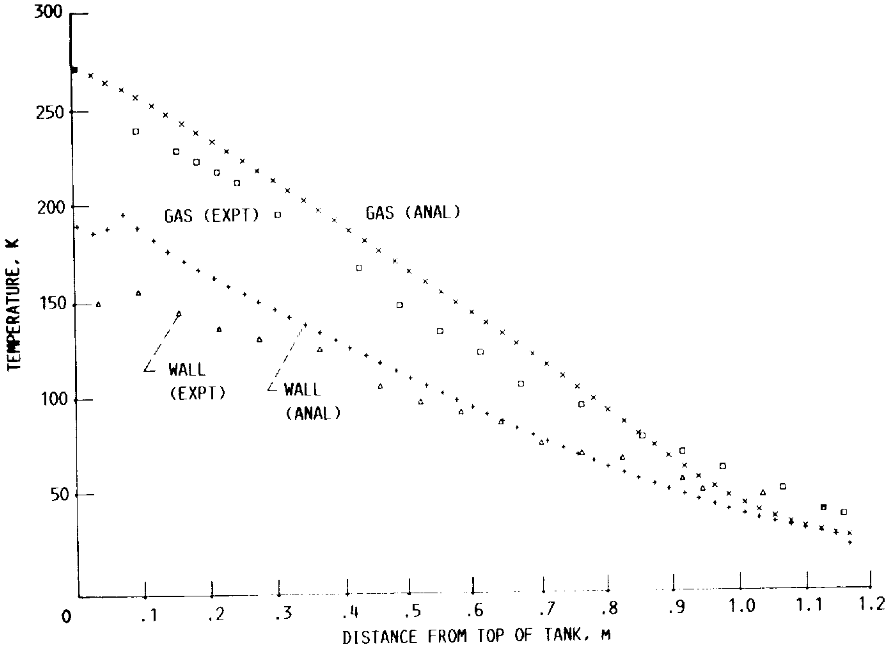

FIGURE 7. - TEMPERATURE PROFILE COMPARISON; H_2 GAS, 261 SEC EXPULSION, RUN 14, NASA TN D-5336.

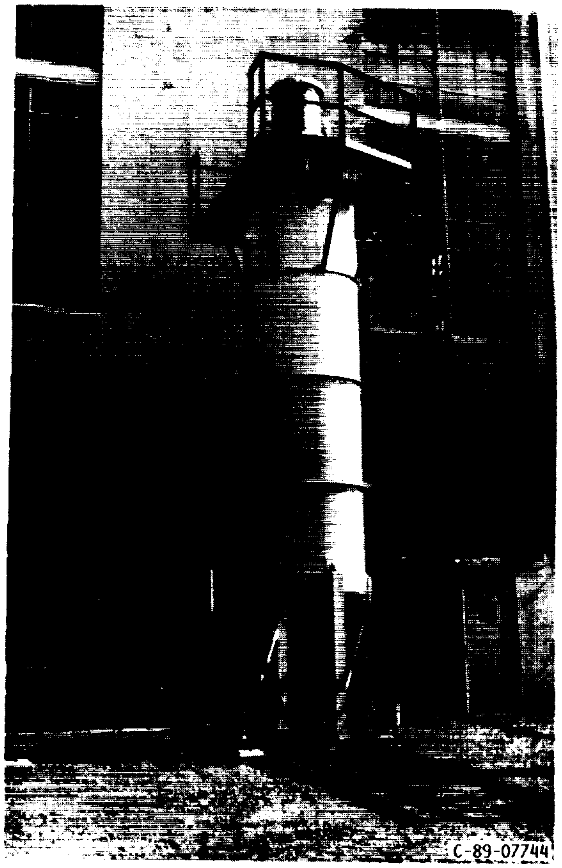

FIGURE 9. - SLUSH GENERATOR TANK INSTALLED AT THE NASA LeRC PLUM BROOK FACILITY.

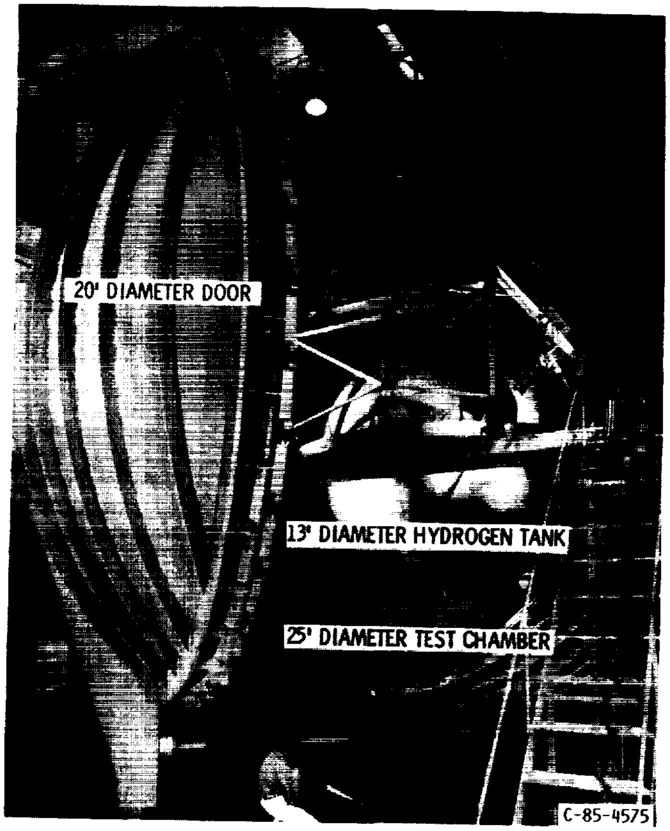

FIGURE 8. - CRYOGENIC PROPELLANT TANK LAB (K-SITE) AT THE NASA LeRC PLUM BROOK FACILITY.

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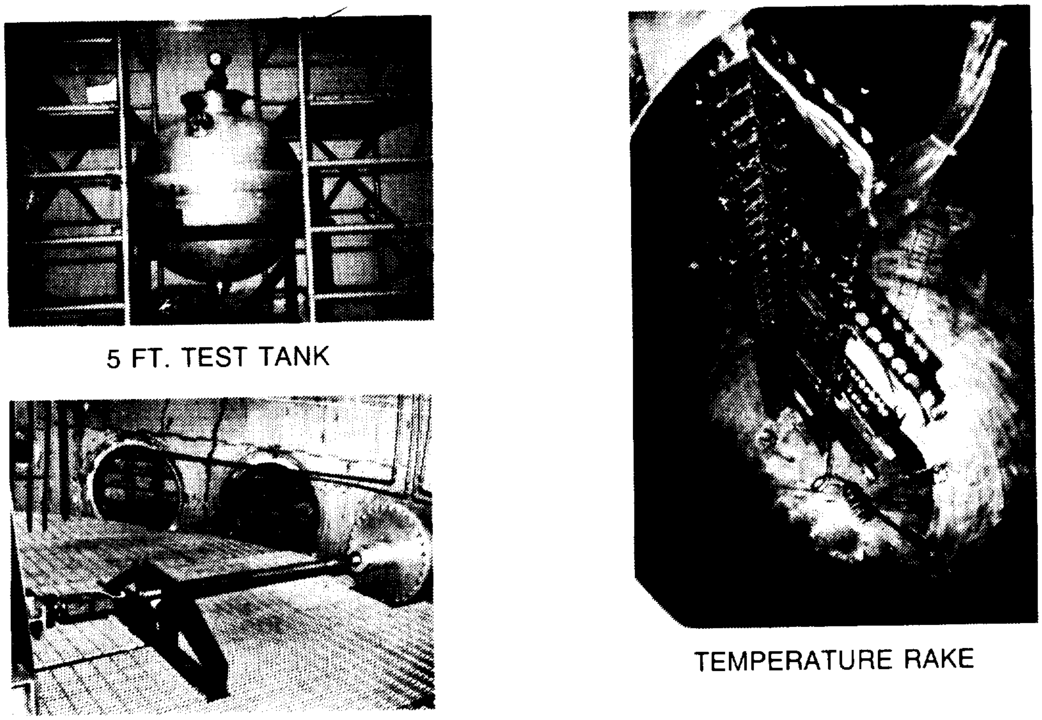
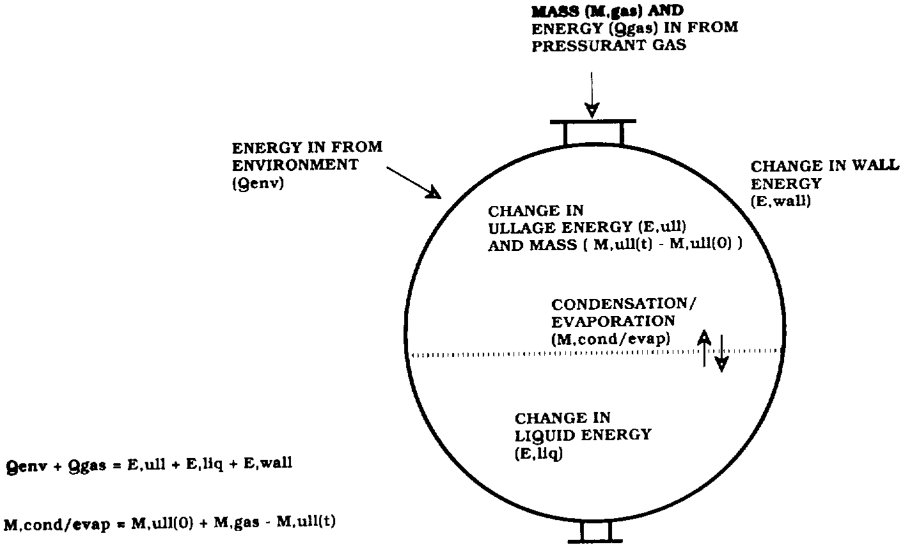

5 FT. TEST TANK

SHAKER

TEMPERATURE RAKE

C-89-8159

FIGURE 10. - SLH_2 TEST HARDWARE.



$Q_{env} + Q_{gas} = E_{,ull} + E_{,liq} + E_{,wall}$

$M_{,cond/evap} = M_{,ull}(0) + M_{,gas} - M_{,ull}(t)$

FIGURE 11. - DATA REDUCTION FOR K-SITE SLUSH HYDROGEN TESTING.

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16. Abstract

The NASP program is giving us the opportunity to reach new unique answers in a number of engineering categories. The answers are considered "enhancing technology" or "enabling technology". Airframe materials and densified propellants are examples of "enabling" technology. The National Aeronautics and Space Administration's Lewis Research Center has the task of providing the technology data which will be used as the basis to decide if slush hydrogen (SLH2) will be the fuel of choice for the NASP. The objectives of this NASA Lewis program are (1) to provide, where possible, verified numerical models of fluid production, storage, transfer, and feed systems, and (2) to provide verified design criteria for other engineered aspects of SLH2 systems germane to a NASP. This program is a multiyear multimillion dollar effort. The present pursuit of the above listed 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 will be a summary of the NASA Lewis overall program plan. The initial implementation of the plan will be unfolded and the present level of efforts in each of the resource areas will be discussed. Results already in hand will be pointed out. The paper will conclude with a description of additionally planned near-term experimental and analytical work.

17. Key Words (Suggested by Author(s))
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