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THE DEVELOPMENT OF PLASMA SYNTHESIS TO PRODUCE PRE-ALLOYED, ULTRAFINE INTERMETALLIC ALUMINIDE POWDERS FOR INJECTION MOLDING

December 1991

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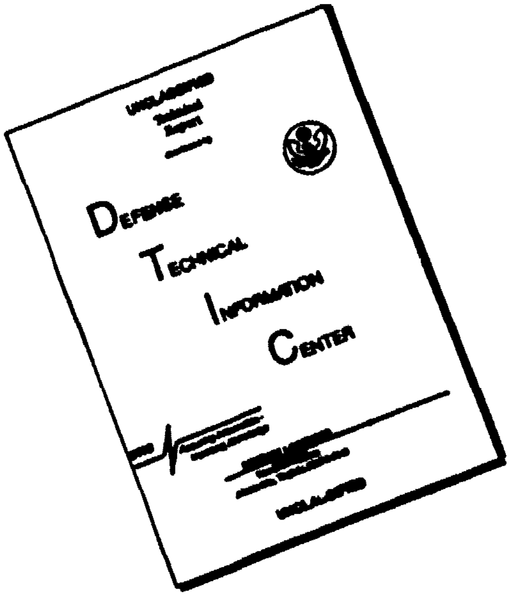
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ABSTRACT

Intermetallics offer significant potential in a variety of military applications. Current processing does not produce significantly small particle sizes to permit the injection molding of complex geometry components. In this Phase I program, the processes of gas phase plasma reaction and plasma initiated SHS reactions (PSHS) were investigated to produce small (<5 µm) intermetallic particle suitable for injection molding. The gas plasma reaction process failed to produce intermetallic powders with a precise stoichiometric control. By contrast, the PSHS process was successful in producing fine (≈5 µm size), irregular shaped powders of NiAl with excellent control of composition. Both stoichiometry control and capability of alloying with ternary additions were demonstrated for the PSHS process and molded powders were sintered to >96% density density in preliminary test which provides the basis for a proposed scale-up under a Phase II program. The PSHS process can be projected to produce particles at attractive economics of $10-50/lb. A novel process termed cathode arc transport (CAT) was demonstrated to produce ultrafine (300-500 nm) spherical intermetallic powders. Excellent compositional control was demonstrated in the CAT transfer process to produce alloy powder. Nanometer intermetallic particles offer significant promise to microstructural control to achieve unusual and enhanced mechanical properties.

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I. ABSTRACT

Intermetallics offer significant potential in a variety of military applications. Current processing does not produce significantly small particle sizes to permit the injection molding of complex geometry components. In this Phase I program, the processes of gas phase plasma reaction and plasma initiated SHS reactions (PSHS) were investigated to produce small (< 5 μm) intermetallic particles suitable for injection molding. The gas plasma reaction process failed to produce intermetallic powders with a precise stoichiometric control. By contrast, the PSHS process was successful in producing fine (≈5μm size), irregular shaped powders of NiAl with excellent control of composition. Both stoichiometry control and capability of alloying with ternary additions was demonstrated for the PSHS process and molded powders were sintered to >96% density in preliminary test which provides the basis for a proposed scale-up under a Phase II program. The PSHS process can be projected to produce particles at attractive economics of $10-50/lb. A novel process termed Cathode Arc Transport (CAT) was demonstrated to produce ultra-fine (300-500nm) spherical intermetallic powders. Excellent compositional control was demonstrated in the CAT transfer process to produce alloy powder. Nanometer intermetallic particles offer significant promise to microstructural control to achieve unusual and enhanced mechanical properties.

II. INTRODUCTION

A. General Background

Performance and weight goals for current and future generations of military systems have spurred the development of improved materials capable of operating at ever increasing stresses and temperatures. While the existing Ni-base superalloys perform exceptionally well up to 1100°C, the density penalty is too severe for many future systems. A host of novel materials including polymer, ceramic, metal and intermetallics are being developed to satisfy the projected need. Intermetallics have a broad base of applications as monolithics and composites. Among the variety of intermetallics, the aluminides have generated considerable interest in the scientific community because of their low density, excellent oxidation resistance and high strength potential. These properties, combined with their low volume diffusion coefficient in the ordered lattice and good creep resistance makes aluminide intermetallics (especially those of nickel and titanium) the most likely candidates for use in next generation of advanced military systems.

Intermetallic phases are compounds of metals with lattice structures considerably different from those of the constituent metals. Unlike metals and alloys, the constituent elements are known to occupy specific positions in the unit cell (for example, either at the unit cell corners or face centers etc.) leading to an 'ordered' structure, hence the name 'ordered alloys'. The tendency for such atomic arrangements is often driven by the lower A-B bond energy than the A-A and B-B bond energies, thereby maximizing the number of unlike (atomic species) neighbors. This lower A-B bond energy creates an unusually stable structure with the melting point of these intermetallics (especially the aluminides) exceeding the melting points of one or both constituent elements. For example, while the melting points of Ni and Al are 1453°C and 660°C, that of NiAl is 1638°C. It is this stable bonding which is believed to be responsible for their high elastic modulus and the exceptionally good modulus retention at high temperatures, the low volume diffusion, good creep resistance and strength at high temperatures. The dislocation dynamics in the ordered lattices are different from conventional metals and alloys and sometimes lead to unusual properties like increasing (rather than decreasing) strength with increasing temperatures.

Although ceramics exhibit equally (if not better) high modulus retention, low volume diffusion, good resistance to environmental degradation, good elevated temperature strength and creep resistance, a significant advantage of intermetallics is their transition from the brittle state to ductile state at high temperatures (the specific temperature depending upon the intermetallic system). Furthermore, their ambient temperature fracture toughness is generally higher than ceramics. Thus, intermetallics are often regarded as exhibiting a compromise behavior between ceramics and disordered alloys (metals).

B. Ductility/Fracture Toughness of Intermetallics

Schulson [1] first proposed the concept of ductilizing intermetallics through grain size refinements. The concept was experimentally demonstrated by Schulson and Barker [2] for Ni-49Al at 400°C (see Figure 1). NiAl deforms by <100> slip [3] which provides only three independent slip systems [4] instead of the five required by von Mises criterion [5] for general plastic deformation. That the grain size refinement approach was able to successfully ductilize an intermetallic which is normally limited by the number of available deformation modes is indicative of the promise for this approach being successful in other similar intermetallics.

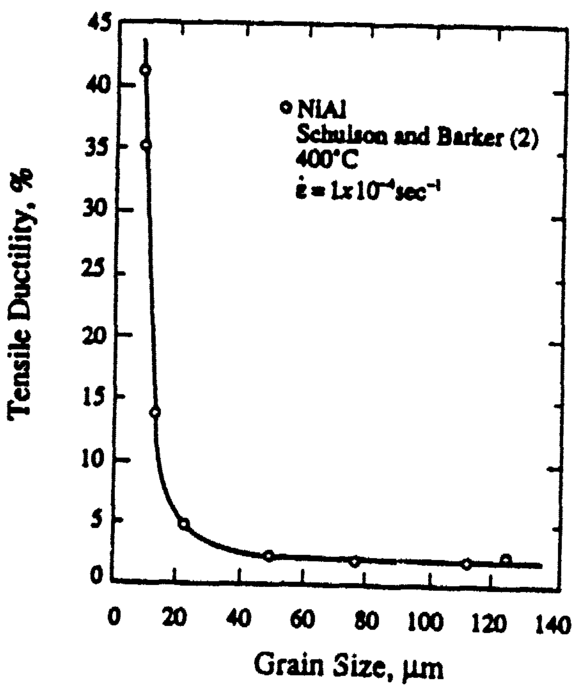


Figure 1. Ductility vs. grain size data for tensile tests in NiAl at 400°C.

Recently, Chan [6] has re-analyzed the elongation vs. grain size data of Schulson and Barker [2] and modeled the deformation behavior through a theoretical analysis of crack instability. The "brittle" to "ductile" transition was indeed shown to be a natural consequence of a decreasing crack size in a fracture process dictated by a critical J (the J-integral) or K (stress intensity) criterion. Chan's analysis suggests that for a constant fracture toughness, the form of the elongation vs. grain size graph was similar to that obtained by Schulson and Barker [2] (See Figure 2). Noebe et al.[7], using the fracture toughness data of NiAl by Reuss and Vehoff [8] and elastic constants data of Harmouche and Wolfenden [9], have also reported a good match between the ductility vs. grain size behavior for powder processed NiAl and

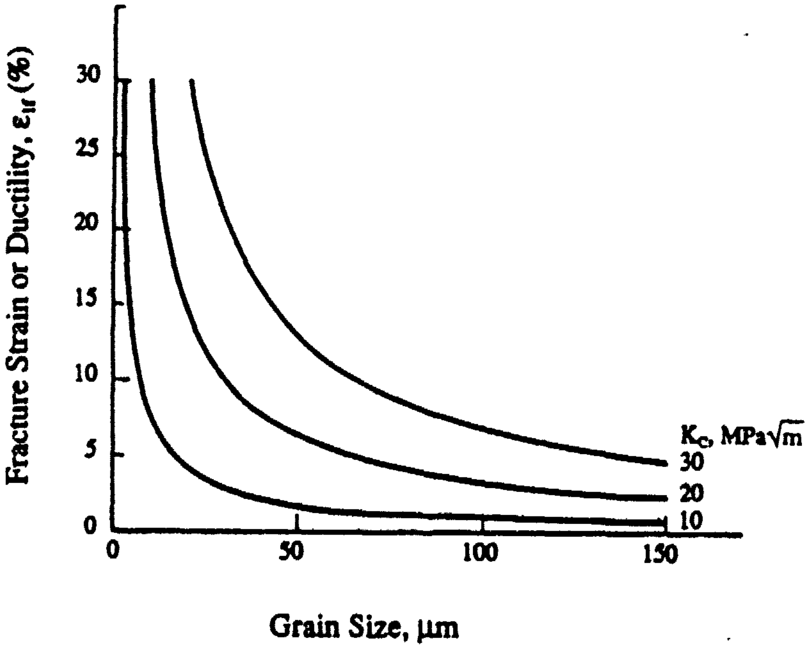


Figure 2. Theoretical grain size dependence of tensile ductility based on J-integral criterion.

Chan's model. Like the cast and extruded NiAl alloy examined by Schulson and Barker, the 'critical' grain size in powder processed NiAl at 427°C was also ≈20μm. At lower temperatures (e.g. at room temperature), however, the predicted critical grain size from Chan's analysis is approximately 0.5μm [10] and is strongly dependent upon the material fracture toughness. Increasing fracture toughness values were predicted to only shift the ductility vs. grain size graph towards higher ductility values (for similar grain sizes) without altering the form, see Figure 2. A closer examination of Schulson and Barkers' data, however, also indicates that observed grain size dependence is larger than that anticipated from sub-critical crack nucleation alone, presumably due to the added benefits of other properties, for example, the fracture toughness and tearing modulus being enhanced by a reduced grain size.

Stonesifer and Armstrong [11] have noted a grain size dependence of fracture toughness of the form

$$K_{IC} = K_{IC0} + ck\, s^{1/2}\, d^{-1/2}$$

where K_{IC0} is the fracture toughness of the single crystal, c is a constant, s is the plastic zone size, k is the Hall-Petch slope (yield strength vs. grain size) and d the grain size. The equation suggests increased fracture toughness for decreased grain sizes. Such grain size dependence for fracture toughness has been experimentally demonstrated for plain carbon steel by Curry and Knott [12] and for austenitic stainless steel by Stonesifer and

Armstrong. Recently, Kostrubanic et al.[13] have also demonstrated significant improvements in measured fracture toughness of the B2 intermetallic Ni-35Al-20Fe processed through a mechanical alloying route. The improved fracture toughness of the intermetallic of the B2 intermetallic was attributed to decreased grain sizes (≈2μm). An improved fracture toughness from decreased grain sizes could only have a beneficial effect on the tensile ductility. Furthermore, Hall-Petch relationships predict improved strength with decreasing grain sizes.

Although it is generally believed that reducing the grain size would impair the creep properties of the material, Whittenberger [14] suggested that for very small grain sizes (of the order of sub-grain size), the creep properties should be improved. In fact, several investigators (Vandervoort et al.[15], Yang and Dodd [16], Whittenberger [14,17]) have already noted the anomalous behavior of improved creep resistance for NiAl with very fine (<15μm) grain sizes. Since NiAl exhibits sub-grain formation during deformation, it was hypothesized that maintaining a stable grain structure smaller than the equilibrium sub-grain size should strengthen the material. Indeed, Vedula et al.[18] have already demonstrated that the flow stress of Ni-50Al at 1027°C for a strain rate of 2×10^{-6} sec^{-1} more than doubled from 15 to 33 MPa when the grain size was reduced from 48μm to 2μm. Unfortunately, this behavior was not consistent since Ni-48Al and Ni-52Al did not exhibit any improvement with decreased grain sizes. Additionally, the existing techniques of improving creep resistance with particulate reinforcements are often hampered by the resulting low temperature embrittlement (or loss of ductility) in the not-so-ductile intermetallic. Should significant improvement in ductility be possible through grain size refinement, some loss in ambient ductility with particulate reinforcements could be tolerated if offset by improved creep resistance.

A second reason for producing fine powders is their improved sinterability in injection molded components. While the low volume diffusion coefficient in the ordered lattice is generally considered beneficial from microstructural stability and creep resistance point of view, it also leads to poor sintered densities. A smaller particle size, besides providing for good mold fill, finer detail, easy removal of binder and isotropic shrinkage during the injection molding operations, will also lead to a higher green density thereby increasing the density of the sintered product.

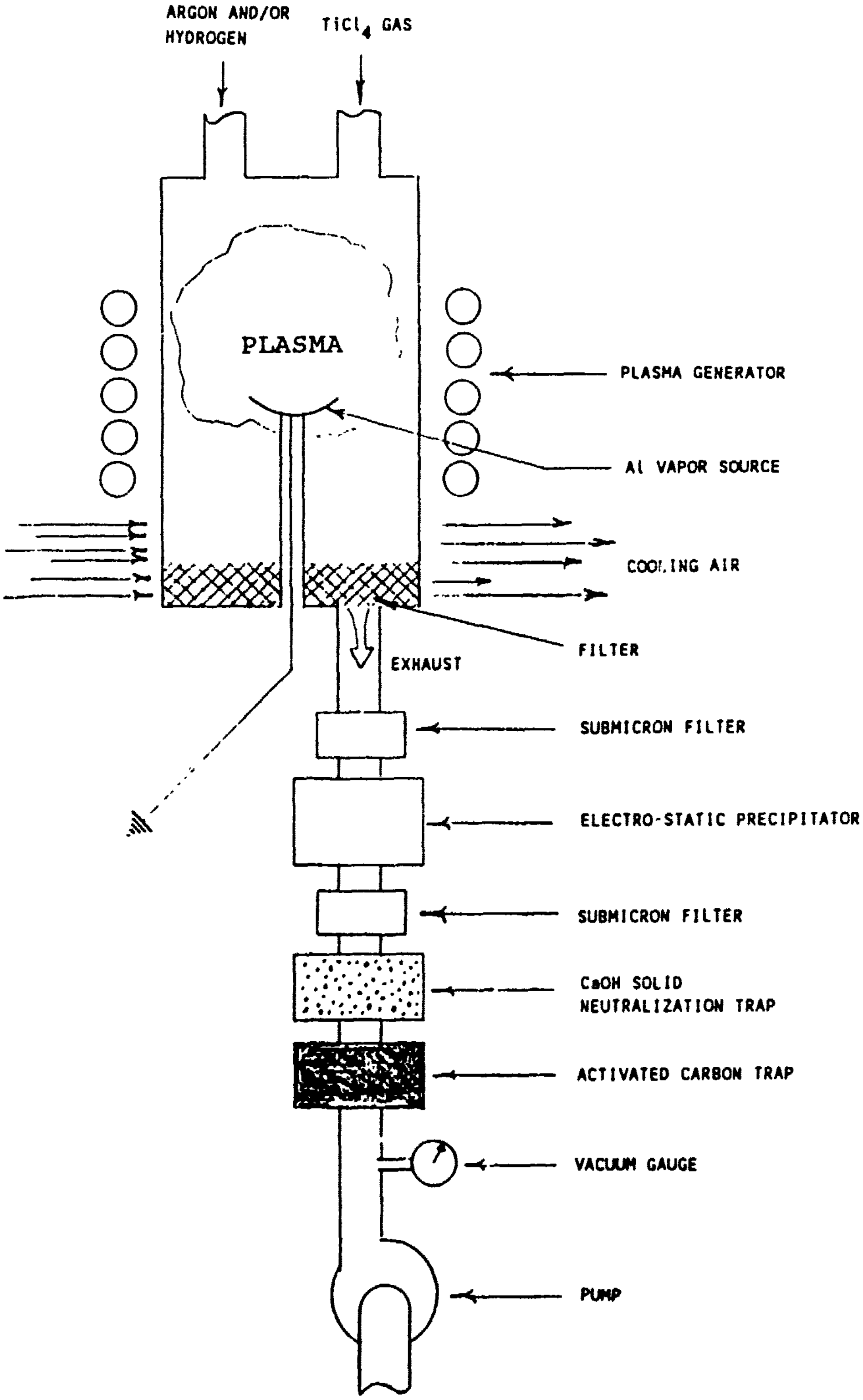
Thus, by reducing the grain size of the microstructure, besides improved sintered densities during injection molding, the room temperature mechanical properties of intermetallics may be enhanced to levels currently unobtainable through conventional processing. Furthermore, such enhancements in room temperature mechanical behavior will not necessarily be achieved at the expense of elevated temperature mechanical properties.

C. Proposed Processes for Intermetallic Powder Production

Two processes were proposed to be investigated for the production of fine (< 20μm) intermetallic powders. The first process, termed the Gas Phase Plasma Reaction, consists of a reaction between a metal chloride and aluminum to produce intermetallic aluminides. In this process, the metal chloride and aluminum are vaporized into an argon and/or hydrogen inductively coupled plasma where the reaction occurs to produce fine powders. A schematic of the experimental set-up for the reaction is shown in Figure 3. The choice of mole fractions of the metal chloride and the aluminum is based on the stability of desired aluminides within any specific temperature range as predicted by thermodynamic calculations. Since the reaction product is quenched from the gas phase, the resulting powder size is in the micron to sub-micron range and spherical in shape. Such powders are generally considered ideal for injection molding. Some of the questions to be answered were if the powder could be produced without contamination from chlorides or other residual metallic impurities and whether the composition of the powder could be controlled.

The second process to be investigated was Self Propagating High Temperature Synthesis, commonly referred to as SHS reactions. Here the metal powders constituents are mixed in a prescribed powder size and reacted using a spark or ignition coil initiation of reaction to produce the intermetallic powders. Once initiated, the reaction proceeds on its own without the need for any external energy sources, driven by the exothermic nature of the reaction. The spark or ignition coil initiation usually results in a wavefront reaction propagation. In a variation to this process, MER discovered that the process can be preferably initiated under the action of an inductively coupled argon plasma. The primary

Figure 3. Experimental Set-up for Gas Phase Plasma Reaction.



differences with the conventionally practiced process are the high rate of heating (the rate of heating has been mentioned by some researchers e.g. Munir) to be an independent variable affecting the reaction and the high thermal content of the plasma which can successfully initiate even weakly exothermic, difficult-to-initiate reactions. For example, the reaction between Ti and Al to produce Ti_3Al is weakly exothermic, and while the reaction cannot be ignited using an ignition coil, MER has demonstrated the production of Ti_3Al using Plasma Initiated SHS reactions (PSHS). A schematic of the PSHS reaction is shown in Figure 4.

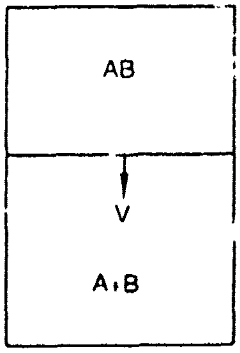


Figure 4. Schematic of the PSHS process.

For the present investigation, it was decided to produce fine powders of the intermetallic NiAl. The phase stability region of NiAl is shown in Figure 5.

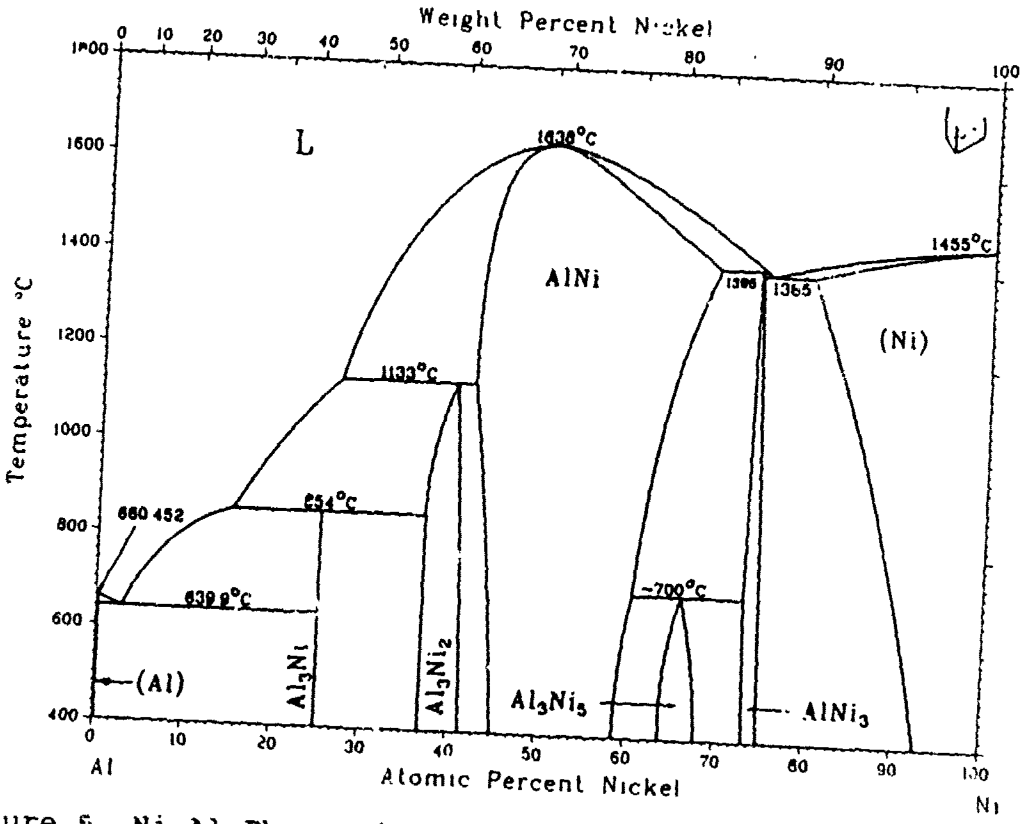


Figure 5. Ni-Al Phase Diagram [19].

D. Properties of Nickel Aluminide

The yield strength of nominally stoichiometric NiAl was noted by Rozner and Wasilewski [20] to be essentially independent of temperature up to 600°C, beyond which the strength was markedly dependent upon temperature. Pascoe and Newey [21] have shown the yield strength of NiAl to be sensitive to the composition; the yield strength was observed to be a minimum for the stoichiometric composition(i.e. Ni-31.4 wt.%Al), increasing with increasing deviations from stoichiometry, with the rate of increase being higher on the Al-rich side than the Ni-rich side. The variation of yield strength with temperature was similar for the stoichiometric and off-stoichiometric alloys although, the 'critical temperature' beyond which the strength decreased sharply, was highest for the stoichiometric composition and decreased with increasing deviation from stoichiometry, similar to the variation of solidus temperature with composition [19], reflecting a dependence of strength on solidus temperature i.e. loss of strength being attributable to increased diffusion activity.

There are no known reports of tensile ductility in NiAl single crystals. Rozner and Wasilewski [20] first reported limited room temperature tensile ductility (≈2.5%) for polycrystalline, near-stoichiometric NiAl, processed through a casting and extrusion route, although the grain size and wet chemical analysis results were not reported. In the studied temperature range of -196°C to 1100°C, the tensile ductility was observed to be essentially constant from room temperature to ≈400°C. The room temperature result was recently reproduced by Hahn and Vedula [22] who reported the grain size to be 11-16 μm and the wet chemical analysis results as Ni-31.6 wt.%Al (Ni-50.3 at.%Al). These results are in sharp contrast to those by Grala [23] who observed no tensile ductility below 600°C. Ball and Smallman [24] studied the mechanical behavior of cast, polycrystalline NiAl (stoichiometric and off-stoichiometric) in compression and reported a brittle-to-ductile transition behavior of ≈0.45Tm. The fracture behavior was noted by Pascoe and Newey [21] as generally intergranular for fine grained polycrystals (≈50μm grain sizes) with an increasing tendency for cleavage fracture with increasing grain sizes. Single crystals were observed to fail by cleavage on {110} planes [21].

The usual slip system for NiAl was identified to be {110}<100>

by Ball and Smallman [13] although Wasilewski, Butler and Hanlon [25] have reported the operation of both (110)<100> and (100)<100> slip in NiAl single crystals. A <100> slip vector provides only three independent slip systems regardless of the number of planes on which slip occurs [4]. Since uniform, volume conserving deformation requires the operation of at least five independent slip systems, often referred to as von Mises criterion [5], the brittleness of NiAl has often been ascribed to the lack of sufficient number of independent slip systems.

Attempts at increasing the number of independent slip systems (that is, changing the slip system to (110)<111>) of NiAl through macroalloying additions, while successful for additions (≈5 at.%) of Cr and Mn, failed to produce any ductility improvements [26]. By contrast, macroalloying NiAl with Fe in work by the principal scientist on this program, produced ≈2.5% elongation and a high yield strength of 800 MPa [27] (compared to the yield strength of 250 MPa and 2.5% elongation for stoichiometric NiAl [22]), but failed to change the slip vector to <111> [27]. It should be noted, however, that grain size refinement still holds appreciable promise for enhancing the ductility/fracture toughness of intermetallics.

Thus, NiAl-based alloys, although attractive due to their excellent oxidation resistance, high stiffness (Young's modulus of polycrystalline alloy: ≈240 GPa [9]), and low density (5.8 for Ni-50at.%Al) for structural applications, are limited by their low ductility (if not outright brittleness) at ambient temperatures.

At intermediate temperatures (≈0.45 Tm), they undergo a brittle-to-ductile transition but also lose strength rapidly with increasing temperatures.

In summary, previous research indicates the possible mechanical property enhancements obtainable by a reduced grain size. Further, since the volume diffusion coefficient is low in the NiAl ordered lattice (and minimum at the stoichiometric Ni-50at.%Al composition), a reduced particle size may improve the sinterability for injection molded articles. To achieve this dual goal of improved mechanical properties and improved sinterability of injection molded components, it is necessary to produce intermetallic powders (NiAl) with very small particle sizes. For practical implementation into military systems it is also necessary to produce alloy powders and the process must be more economical than the current rapid solidification particle processes which, in addition to high cost, produce particles too large for injection molding.

III. PHASE I RESEARCH OBJECTIVES

The objective for this Phase I investigation was the development of an inexpensive process for the production of pre-alloyed, ultrafine intermetallic aluminide powders for injection molding applications. The specific objective was the investigation into Gas Phase Plasma Reactions and Plasma Initiated SHS reactions as possible routes to the production of intermetallic powders. The primary emphasis of the Phase I program was to be

- the identification of process variables
- the demonstration of ternary element alloying capability for the intermetallic powders
- the demonstration of the ability to exercise control over the composition of intermetallic powders
- the demonstration of ability to produce contamination (second phase) free intermetallic powders.

The program objective included supplying the program Technical Monitor of a small amount of ultra-fine intermetallic powders produced through either process. At the conclusion of the Phase I investigation, judging by the results obtained from both processes, one of the processes was to be scaled up under the Phase II program. The Phase II program was also intended to be a more complete investigation into the effect of process variables on intermetallic particle size and yield.

IV. RESEARCH PROCEDURES

The processes and techniques utilized to produce ultrafine pre-alloyed intermetallic powder and the methods of evaluation are given in the following sub-sections. The processes were to be investigated with respect to the following powder characteristics (listed in increasing order of importance):

- shape of powder
- size of powder
- purity of powder
- compositional control
- ternary and quaternary alloying capability

A. Gas Phase Plasma Reaction

Figure 3 is a schematic illustration of the reactor utilized for the Gas Phase Plasma reactions. The setup consists of a vacuum chamber (quartz tube) placed within an induction coil with a vacuum being drawn from the bottom; inert (argon) gas is introduced from the top to allow the gas to settle by its weight thereby displacing the entrapped air molecules. Using the above set-up, a vacuum of up to 10 millitorr can easily be obtained which is sufficient for the present investigation. Since the nickel aluminide was to be synthesized through a gas phase reaction of nickel chloride with aluminum, both anhydrous $NiCl_2$ and elemental Al were placed within the RF field in graphite crucibles. The low volatilization temperature of $NiCl_2$ makes the reaction possible.

Since a control of the purity and composition of the intermetallic powder requires a control over the input ratio of $NiCl_2$ and Al, and because elemental Al powder was discovered to be impossible to transfer successfully at a controlled rate using a laboratory scale set-up, controlled introduction of reactants was attempted through a design of the crucibles. At a given temperature (assumed to be the crucible temperature), the vapor pressures of both $NiCl_2$ and elemental Al were determined and the rates of evaporation (thereby the rate of introduction of reactants into the plasma) were compensated using different exposed areas of crucibles containing the reactants. One problem with this approach was discovered to be the different coupling efficiency in the induction field of differently sized crucibles. Hence, while the $NiCl_2$ volatilized rapidly (and was soon exhausted), the Al barely melted or its low temperature did not produce sufficient vapors. This problem of control over composition of gaseous mixture led to abandonment of this approach of controlled vapor release of the reactants in the Argon plasma.

The alternate approach to this gas phase reaction was introduction of reactants in a powder form in a controlled ratio and heating of the powdered mixture at a high rate to ensure volatilization of both constituents simultaneously. While this approach worked in principle, as will be presented later, the results were disappointing, due to a lack of precise control of the reactant vapor mixture in the plasma. Although nickel aluminide (NiAl) was successfully produced by this approach, the intermetallic was contaminated with residual chloride, Ni, Al or

Ni_3Al impurity.

B. Plasma Initiated SHS Reactions

Self-propagating high temperature synthesis (SHS) reactions are well known [28] and have been extensively investigated to produce a variety of materials. Typically, the materials formed from a SHS reaction are a loosely bound, partially sintered porous mass. The general criterion for SHS reactions is that $\Delta H/C_p \geq \approx 2000$°K in order for the reaction to be self-sustaining. Another criterion is that the adiabatic temperature T_{ab} of combustion should be $\geq \approx 1800$°K. The adiabatic temperature of NiAl has been reported to be 1923°K [29] which satisfies the above criteria. For weakly exothermic reactions like Ti_3Al, the reaction will not be self-sustaining unless the ambient were raised to or near these temperatures. The SHS reaction is typically initiated utilizing a hot wire and the reaction propagates along a wavefront at a speed in the range of 0.15-15 cm/sec until the reaction body is reacted.

Reactions that have $T_{ab} < 1800$°K and/or $\Delta H/C_p \leq 2000$ are weakly exothermic and will not self-ignite unless external heat is provided to raise the ambient such that the ignition (ambient) temperature plus T_{ab} exceeds 1800°K. In case of Ti_3Al, the ambient must be raised above the melting point of aluminum and can be as high as 1000-1200°K. In case of NiAl, however, the reaction would be expected to be self-sustaining. Induction heating at lower frequencies, e.g. at 476 kHz was equivalent to resistance heating in that the reaction would initiate only when the thermal rise was high enough that $T_{ab} \geq 1800°K$. However, for a frequency in the range 3-8 MHz in an argon atmosphere, a plasma is generated that instantly initiates the reaction (weakly exothermic or not) uniformly throughout the body.

Plasma initiation of an SHS reaction is achieved by placing the body for reaction in an argon plasma (or any other gas) that immediately initiates the reaction uniformly and simultaneously throughout the body. Since the reaction is initiated uniformly throughout the body, <u>in-situ</u> compaction is readily achievable by application of pressure, similar to hot forging that produces net shapes. MER developed the plasma initiated SHS process prior to this program which is in the process of patent application. The PSHS reaction has been demonstrated with a number of ceramic and intermetallic systems including borides, carbides, aluminides of nickel, niobium and titanium etc. For the purpose of the present program, however, attention was directed towards producing a porous reacted mass for easier (subsequent) de-agglomeration into powders. Also, the primary focus was the production of impurity free intermetallic powders and alloying of these intermetallics with ternary elements.

In this program, the nickel and aluminum powders used were an average of 3μm in diameter. The powders were mixed (both wet mixing in toluene and dry mixing were investigated) and pelletized at different pressures (typically in the range 15ksi-25ksi); two different pellet sizes (½" and ¼" diameter pellets) were investigated. Different Ni-to-Al ratios and weight fractions of diluents (carbon and previously reacted NiAl) were investigated. The argon plasma was generated using an induction coil ≈3" in diameter, ≈4" long with 6 turns; the phase II program will investigate the effect of different field strength on the reaction. The pellets were reacted in the argon plasma until completion (typically ≈1 minute) and subsequently de-agglomerated into powders using a 4" diameter ball mill. We have recently finished the construction of a 12" diameter ball mill which is expected to increase the efficiency of the deagglomeration process. The resulting powder was screened and examined using SEM and x-ray diffraction.

C. Cathode Arc Transport

Another plasma process with great versatility that was investigated in this program is often referred to as the low temperature cathode arc transport process. Originally developed as a coating process, in this program the process was adapted for producing ultra-fine, spherical intermetallics powders.

The original process as typically utilized to deposit coatings is shown in Figure 6. The process consists of striking an electric arc between two or more electrode materials to be vaporized under a vacuum of 10^{-2} to 10^{-8} torr. The DC electric current can vary from 50 to several hundred amperes with voltages in the range of 75 to 120 volts. This process, accordingly, necessitates a low voltage high current arc unlike the atmospheric plasma where several hundred volts may be required [30]. The unique feature of this process is that the plasma is generated by small (10^{-8} to 10^{-4} m in diameter) arc spots that move rapidly and randomly over the cathode material [31], with the temperature of these spots reaching as high as 10,000°K. The arc, therefore, traverses the surface of the cathode and vaporizes it into a high energy plasma. A high percentage (up to 100%) of the materials eroding from the cathode arc are emitted as ions [32] with high kinetic energies [33] in the range of 10-100 eV. These ions, therefore, travel at considerable velocities, estimated to be as high as 10^4 m/sec [34]. In addition, most of the ions tend to travel away from the cathode, and can be condensed to very fine particles in the cooler regions of the plasma, with compositions the same as the source material (because of the super high temperature of the arc spots). Accordingly, low temperature cathode arc transport processes offer significant advantages over other plasmas, E-beam evaporation and sputtering since no compositional fractionation occurs during the process.

In this investigation, hot extruded intermetallic rods were obtained from NASA Lewis Research Center (courtesy of Dr. M.V. Nathal) and mounted in a graphite holder; the graphite holder was attached to the cathode terminals. The cathode arrangement was enclosed within a quartz cylinder to allow deposition on the walls in the form of loose powder. A refractory metal (molybdenum) was used as the anode due to its high thermal resistance. The chamber was pumped down using both mechanical and diffusion pumps to different pressures (as desired). The minimum chamber pressure investigated was 10 mtorr. For higher chamber pressures, following the pump-down process, the chamber was backfilled with argon to the desired pressure level. The maximum pressure investigated was 1 atmosphere. The initial arc was struck using a vertical oscillatory contact arrangement. Once initiated, the process is self-sufficient and requires little supervision. A variety of input power was investigated (although more detailed investigation is required which will be undertaken during the Phase II program). Typical runs were of approximately 10 minutes duration. The cathode design was important for yield considerations and needs to be investigated further. At the end of the run, the loose powder was scraped off from the quartz side walls enclosing the cathode. X-ray diffraction and x-ray microanalysis indicated that there was no contamination from the Mo anode or the graphite holder.

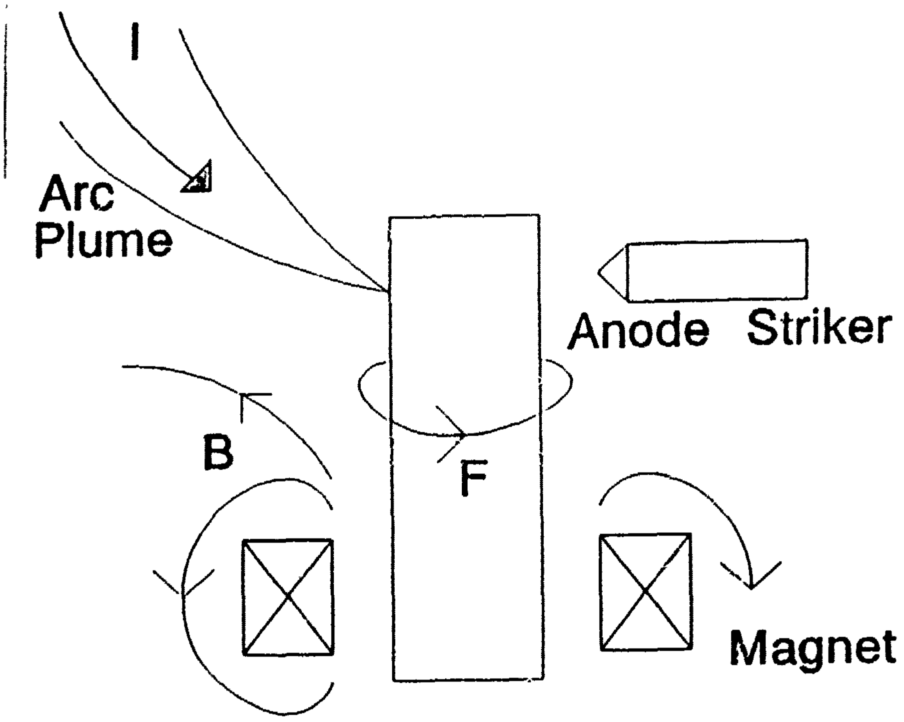


Figure 6. Schematic Set-up for the Cathode Arc Transport Process.

D. Powder Characterization

1. X-ray Diffraction

Characterization of powder purity (whether single phase or not) was performed by examining the powder diffraction pattern over the angular range 25° to 70° (two-theta angles) using a Philips diffractometer. The powder was carefully loaded into the specimen holder while ensuring that the powder surface level was coplanar with the sample holder surface. This process ensures the powder diffraction surface to lie along the diffractometer circle at all times (failure to satisfy this condition results in peak shifts). No binder was necessary to hold the powder in the sample holder over the measured 2-theta range. For 2-theta angles higher than 70°, however, a binder is usually necessary to maintain the powders in their position. Since the four primary peaks of NiAl lie within the 2-theta range of 30-65°, the adopted angular range was adequate for phase identification. Occasionally, electrical noise led to spurious peaks, which are usually characterized by a sharp rise and gradual fall in signal. That any peak is a spurious peak (electrical noise) was confirmed by re-scanning the region at a slower rate. The recorded data was analyzed according to conventional methods.

2. SEM

Secondary electron imaging was utilized primarily to examine the shape and size of intermetallic powders, measure their composition (qualitatively) using Energy Dispersive Spectroscopy (EDS) and examine the microstructure of sintered compacts. In the absence of standards (of compositions similar to the alloys examined here), and because of the large activation volume (beam spreading) beneath the electron probe, EDS analysis was limited to only a qualitative analysis. An incident voltage of 30 kV was used which was much higher than the ionization potential of all elements examined here. Backscatter electron imaging (where heavier atomic number elements appear brighter in the image), and x-ray dot map imaging were used to identify any gross segregation of elements in sintered compacts. Powder specimens were mounted by placing a small drop of alcohol on an aluminum stub and dropping a small quantity of powder onto it; the alcohol disperses the powder while evaporating, leaving behind a well dispersed powdered specimen. The powders were subsequently gold-coated in a vacuum plasma chamber prior to examination in the SEM.

E. Sintering Experiments

Sintering experiments on the powders produced through the PSHS process were performed by cold-pressing pellets at room temperature and sintering these pellets at near-solidus temperatures. For NiAl powders, since the melting point of stoichiometric NiAl is 1638°C, a sintering temperature of 1550°C was chosen to prevent any melting from temperature over-shoot. The pellets were sintered in a reducing atmosphere (a graphite furnace) to prevent significant oxidation. The sintering time was limited to five hours. The sintered pellets were metallographically polished and examined in a SEM and their density measured according to the existing ASTM standards.

V. PHASE I ACCOMPLISHMENTS

A. Gas Phase Plasma Reaction

The first step in the production of intermetallic powders through gas phase plasma reaction is thermodynamic predictions defining the process boundary conditions, i.e. the pressure and temperature for a given starting stoichiometry. The thermodynamic calculations were performed using a modified NASA code. Phase stability of different phases based on Ni and Al (e.g. Al or Ni in gaseous, liquid or solid state, NiAl, Ni_3Al, Ni_2Al_3 or their multiphase mixtures) were calculated using a variety of pressure conditions (with pressures varying from 10 to 1.0×10^{-6} atm and temperatures varying from 900°C to 2200°C). Some of the reaction conditions (pressures in excess of 1 atm. or below 0.1 atm) were calculated only for a better understanding of phase stability tendencies and are impractical for the present set-up (quartz tube), although they may be achieved using more specialized set-up like high pressure cells or high vacuum chambers. The calculations were carried out as follows: starting with a given stoichiometry (equimolar, Ni-rich or Al-rich mixture of Ni and Al), the thermodynamic stability of different phases were calculated for a given pressure over a range of temperatures. For the same given stoichiometry, multiple pressures were investigated. This is a pseudo-3-D representation of the stabilities of different phases over a pressure-temperature domain. The results describing the phase stability of NiAl are summarized graphically in the Figure 7, the complete printouts of the thermodynamic runs are attached in the APPENDIX I.

Figure 7a.

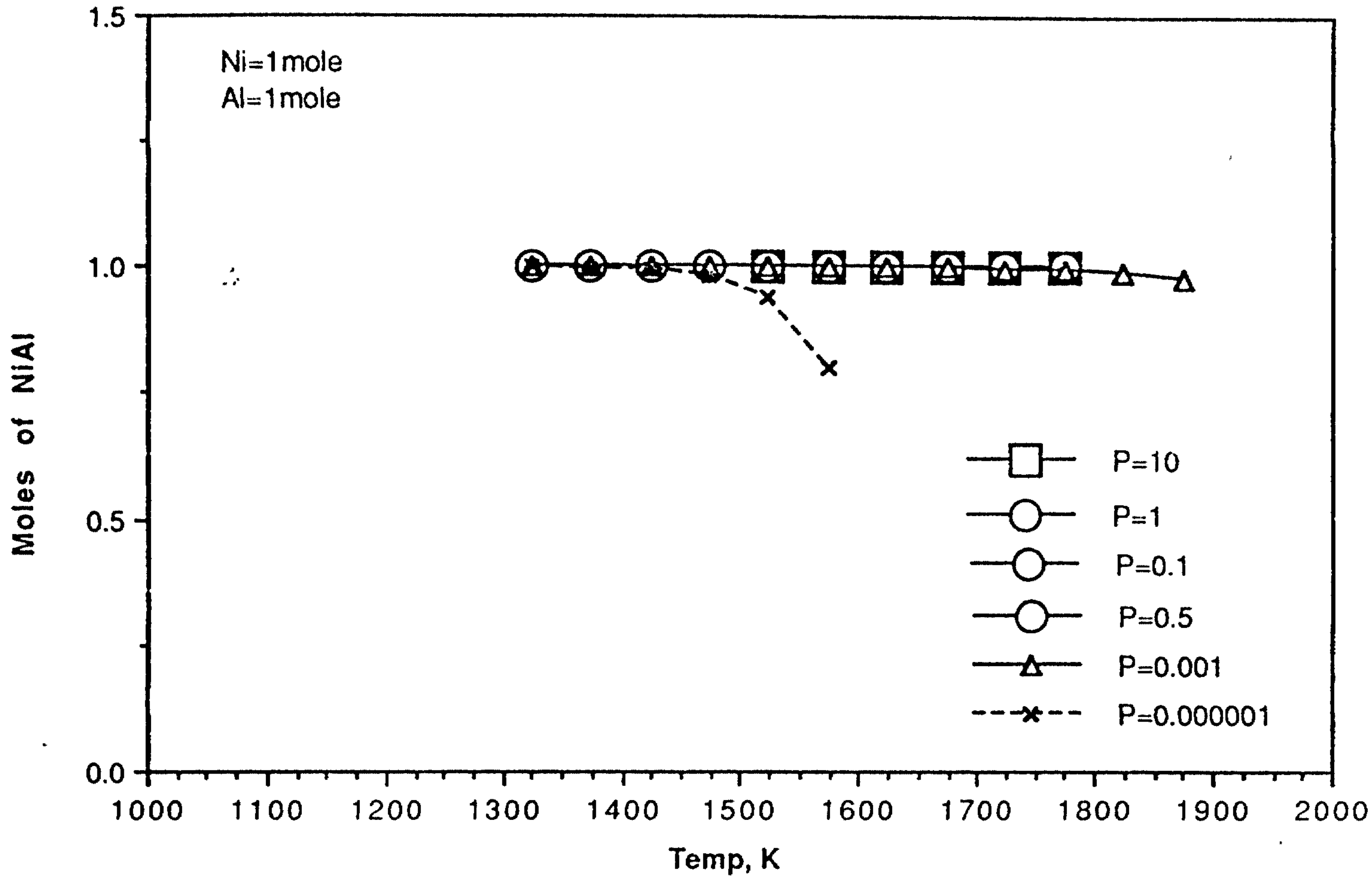


Figure 7. Thermodynamic stability of NiAl in the gas phase reaction for stoichiometric, Ni-rich and Al-rich starting stoichiometries. (a) stoichiometric Ni:Al::1:1; (b) Ni:Al::2:3 (c) Ni:Al::2:4 (d) Ni:Al::3:2 (e) Ni:Al::4:2. Pressures investigated ranged from 10 atm to 10^{-6} atm while temperatures ranged from 2473K to 1173K.

Figure 7b.

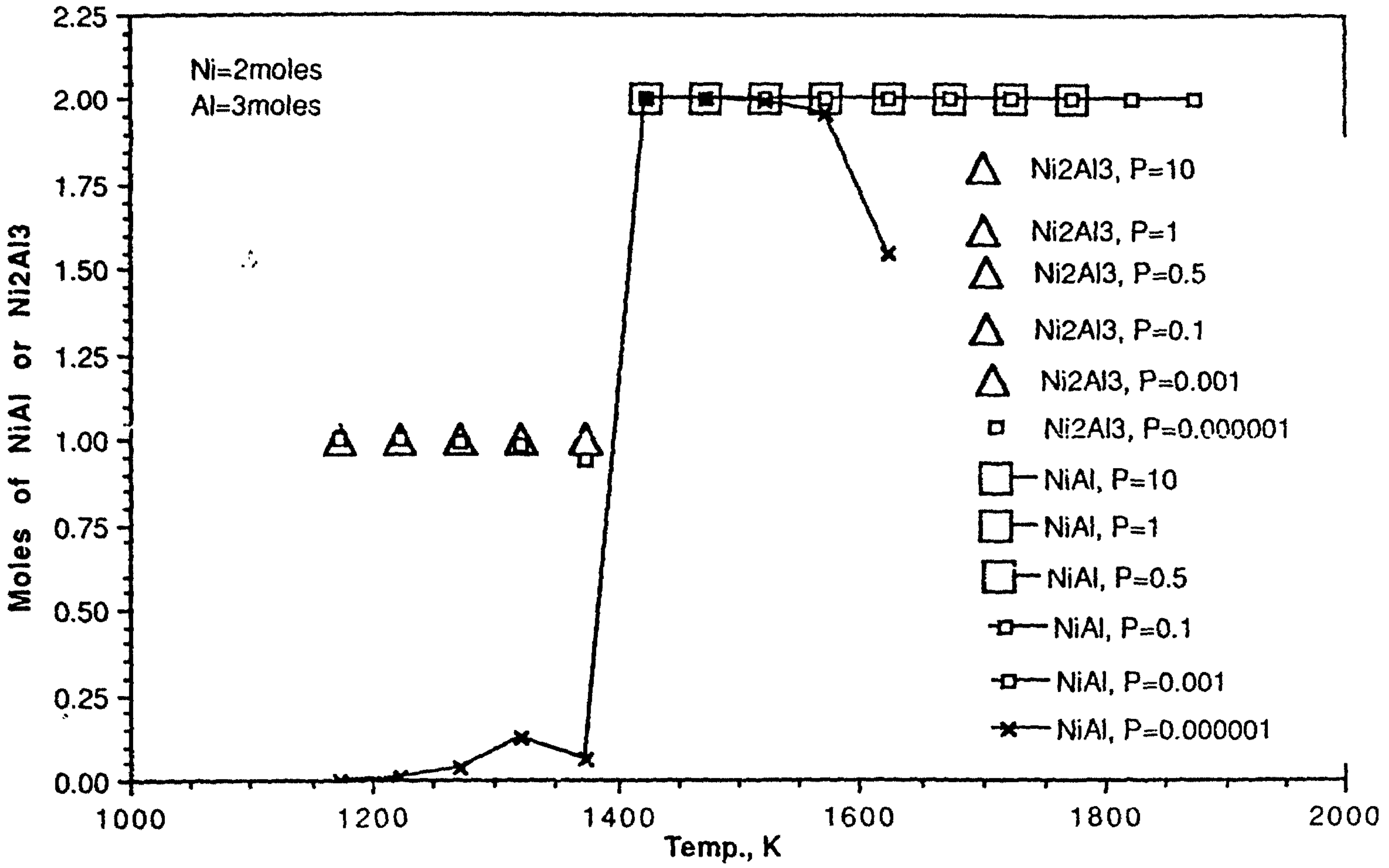


Figure 7. Thermodynamic stability of NiAl in the gas phase reaction for stoichiometric, Ni-rich and Al-rich starting stoichiometries. (a) stoichiometric Ni:Al::1:1; (b) Ni:Al::2:3 (c) Ni:Al::2:4 (d) Ni:Al::3:2 (e) Ni:Al::5:2. Pressures investigated ranged from 10 atm to 10^{-6} atm while temperatures ranged from 2473K to 1173K.

Figure 7c.

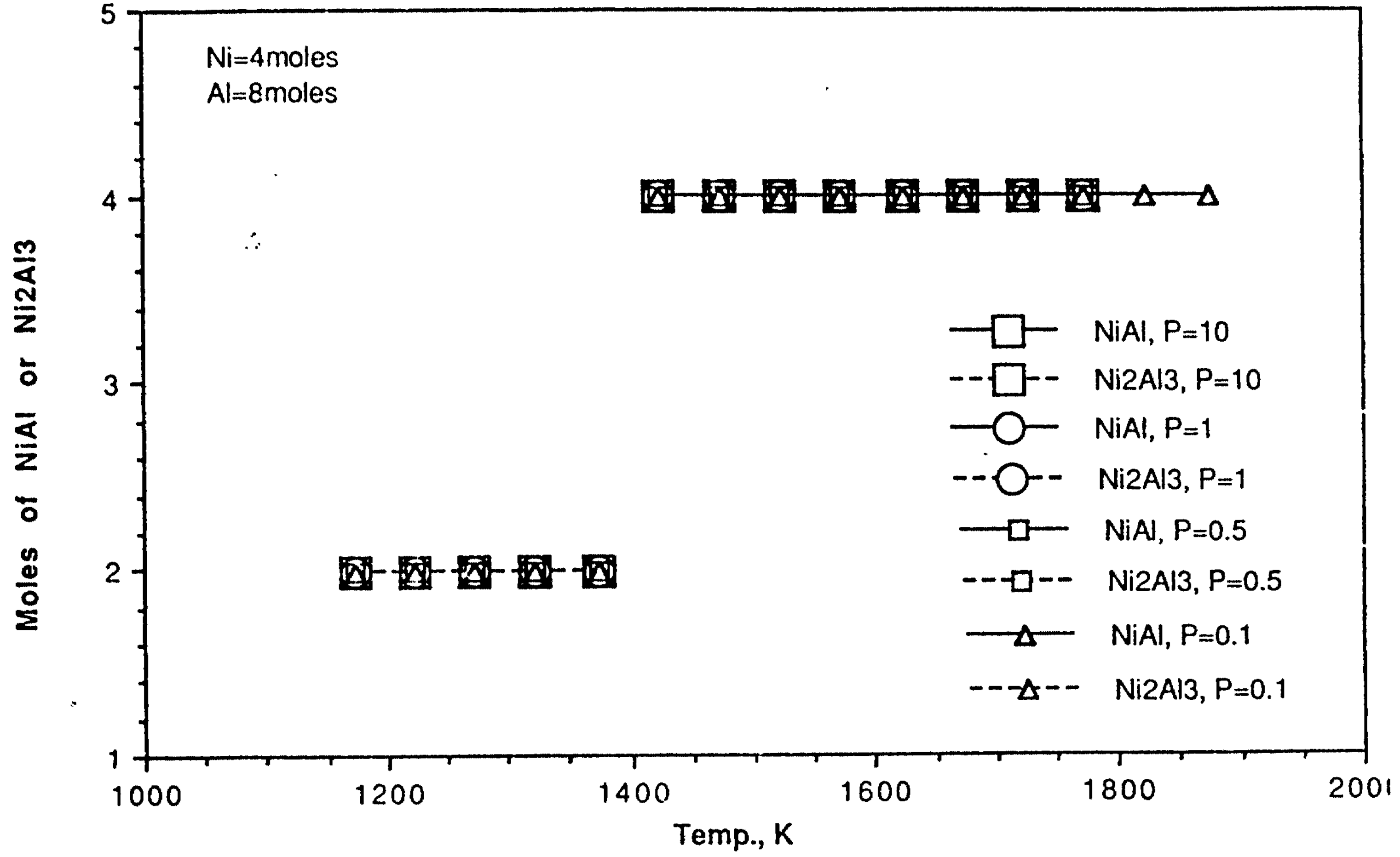


Figure 7. Thermodynamic stability of NiAl in the gas phase reaction for stoichiometric, Ni-rich and Al-rich starting stoichiometries. (a) stoichiometric Ni:Al::1:1; (b) Ni:Al::2:3 (c) Ni:Al::2:4 (d) Ni:Al::3:2 (e) Ni:Al::5:2. Pressures investigated ranged from 10 atm to 10^{-6} atm while temperatures ranged from 2473K to 1173K.

Figure 7d.

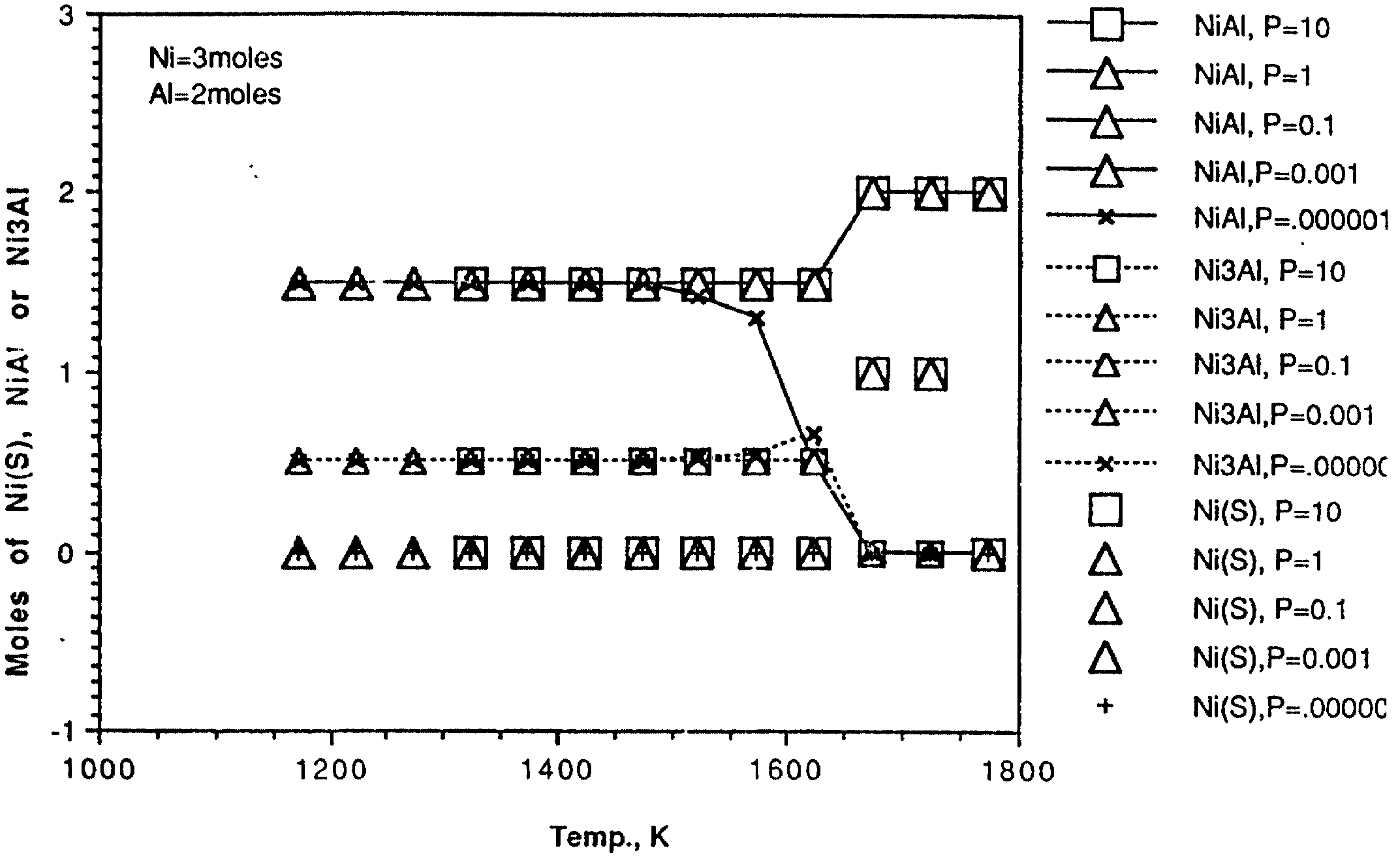


Figure 7. Thermodynamic stability of NiAl in the gas phase reaction for stoichiometric, Ni-rich and Al-rich starting stoichiometries. (a) stoichiometric Ni:Al::1:1; (b) Ni:Al::2:3 (c) Ni:Al::2:4 (d) Ni:Al::3:2 (e) Ni:Al::5:2. Pressures investigated ranged from 10 atm to 10^{-6} atm while temperatures ranged from 2473K to 1173K.

Figure 7e.

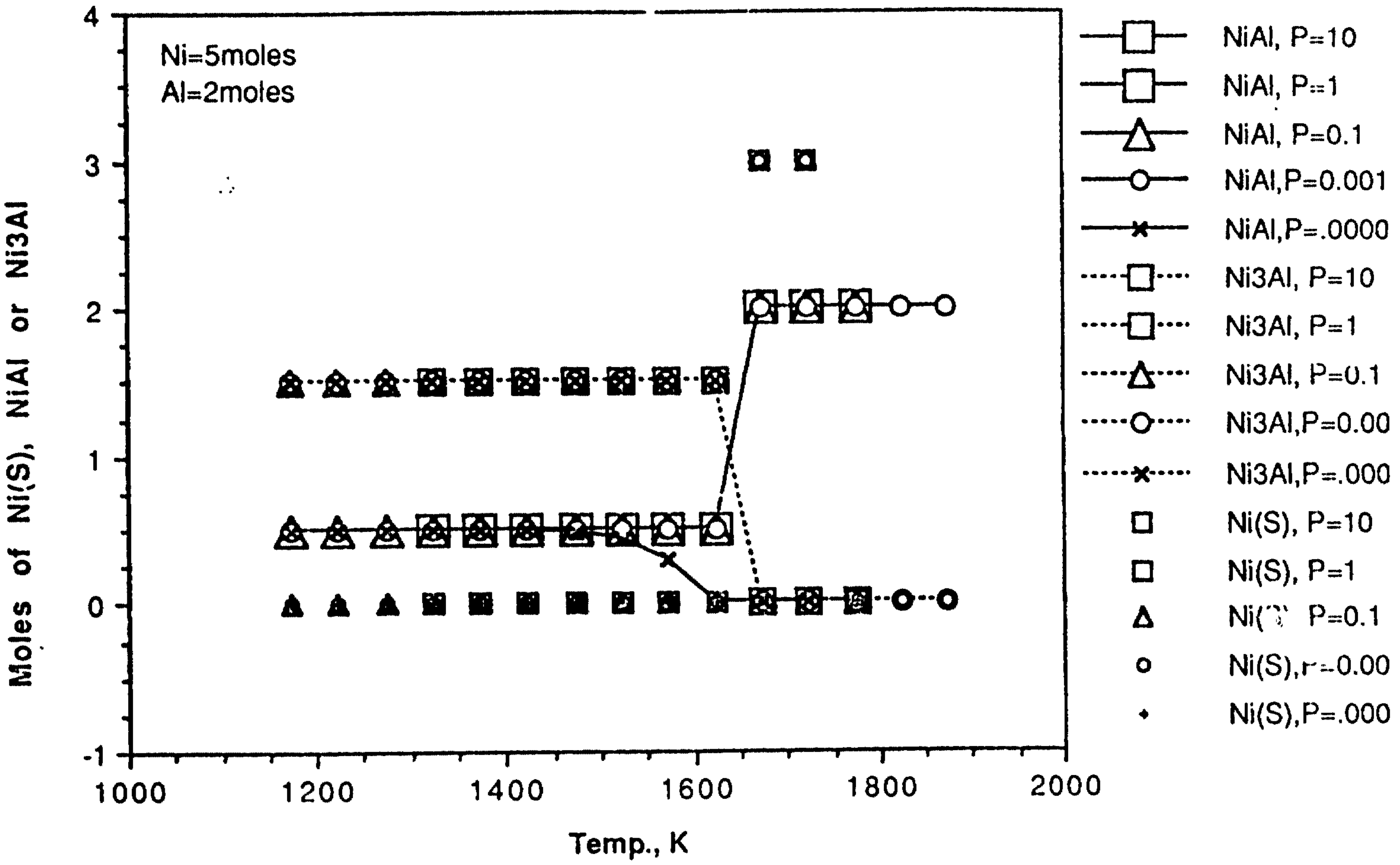


Figure 7. Thermodynamic stability of NiAl in the gas phase reaction for stoichiometric, Ni-rich and Al-rich starting stoichiometries. (a) stoichiometric Ni:Al::1:1; (b) Ni:Al::2:3 (c) Ni:Al::2:4 (d) Ni:Al::3:2 (e) Ni:Al::5:2. Pressures investigated ranged from 10 atm to 10^{-6} atm while temperatures ranged from 2473K to 1173K.

Figure 7a describes the phase stability of NiAl for equimolar starting stoichiometry (Ni:Al::1:1). It should be noted that 1.0 moles of NiAl contains 1 mole of Ni and 1 mole of Al. It is also interesting to note that the stability (temperature range over which only NiAl phase is thermodynamically stable) of NiAl increases with decreasing pressures (with the exception of very low pressures like 10^{-6} atm). Increasing Al enrichment stabilizes the phase Ni_2Al_3, also, a lower pressure $(0.001<P<0.1)$ stabilizes NiAl. The most important conclusion from the above thermodynamic calculations is that, for Al-rich powder mixtures, NiAl is stable over the temperature range 1423°K-1773°K irrespective of starting stoichiometry (Ni:Al ratios of 1, 0.66 or 0.5), the pressure being maintained at ≈0.1 atm. This would partly alleviate the difficulty in introducing controlled compositions of gaseous Ni and Al phases into the plasma. Thus, Al-enriched starting powder mixtures were also investigated. A chamber pressure of 0.1 atm is quite easily obtained.

The gas phase plasma reaction, consisting of evaporating Al metal into a 450kHz argon plasma and simultaneously injecting gaseous $NiCl_2$, was demonstrated to produce spherical, fine particled intermetallic NiAl powders. The powders, however, were laced with impurities of chloride, Ni, Al or Ni_3Al. The problem was deduced to be the uncontrolled evaporation of Al into the plasma. Since the controlled introduction of Aluminum powder into the argon plasma was difficult using laboratory scale set-up (such powders feeders are available only on a larger scale), the alternative approach was to control the stoichiometry of gaseous species in the plasma by adjusting the evaporation rates. The vapor pressure of an element is given by

$$P = n \sqrt{(M\ T)} / (44.33\ a\ t)$$

where P is the vapor pressure in atmospheres, M the molecular weight, n the number of moles, T the temperature in Kelvin, t the time and a the evaporation area in square centimeters. At a temperature of 1800°K, which is slightly below the melting point of NiAl (1911°K), the vapor pressures of Ni and Al are, respectively, 10^{-2} and $6.5\text{x}10^{-1}$ atm, see Figure 8. The rationale behind the choice of a reaction temperature of 1800°K is to allow sufficient evaporation for enhanced yield, however, following reaction between Ni and Al in gaseous state to produce NiAl, the resulting product will be immediately quenched to its solid form. The precipitation of NiAl from gaseous phase reactions, thus, by virtue of homogeneous nucleation, are expected to produce fine-scaled yet spherical intermetallic powders. To produce NiAl of equimolar composition, we set n_{Ni} and n_{Al} equal. Hence,

$$(P_{Al}\ a_{Al}) \sqrt{(M_{Ni}\ T_{Ni})} / (\sqrt{(M_{Al}\ T_{Al})}\ P_{Ni}\ a_{Ni}) = 1$$

$$a_{Ni} = 96\ a_{Al}$$

This result is logical since the lower melting point element, Aluminum, is expected to have a higher vapor pressure than the higher melting point element Ni at a given temperature. Consequently, the surface area of Ni needs to be higher to introduce equal moles of Ni and Al into the gas plasma.

A crucible was designed to compensate for the different rates of evaporation of Ni and Al and is shown in Figure 9. The Al powder or solid rod is placed at the center of the crucible with Ni

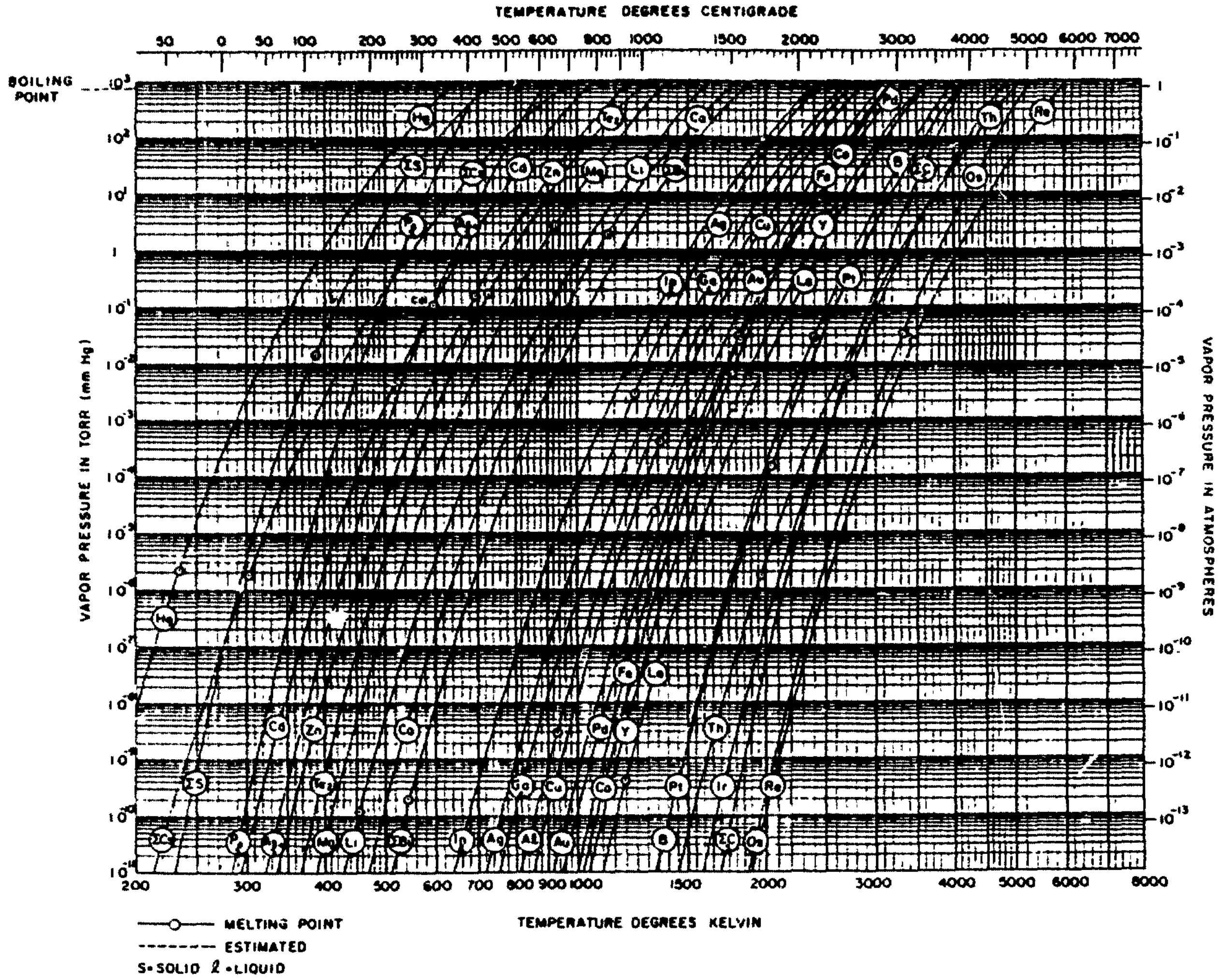


Figure 8. Vapor pressure curves of metals (from "The Characterization of High Temperature Vapors", John L. Margrave, Editor, Appendix A).

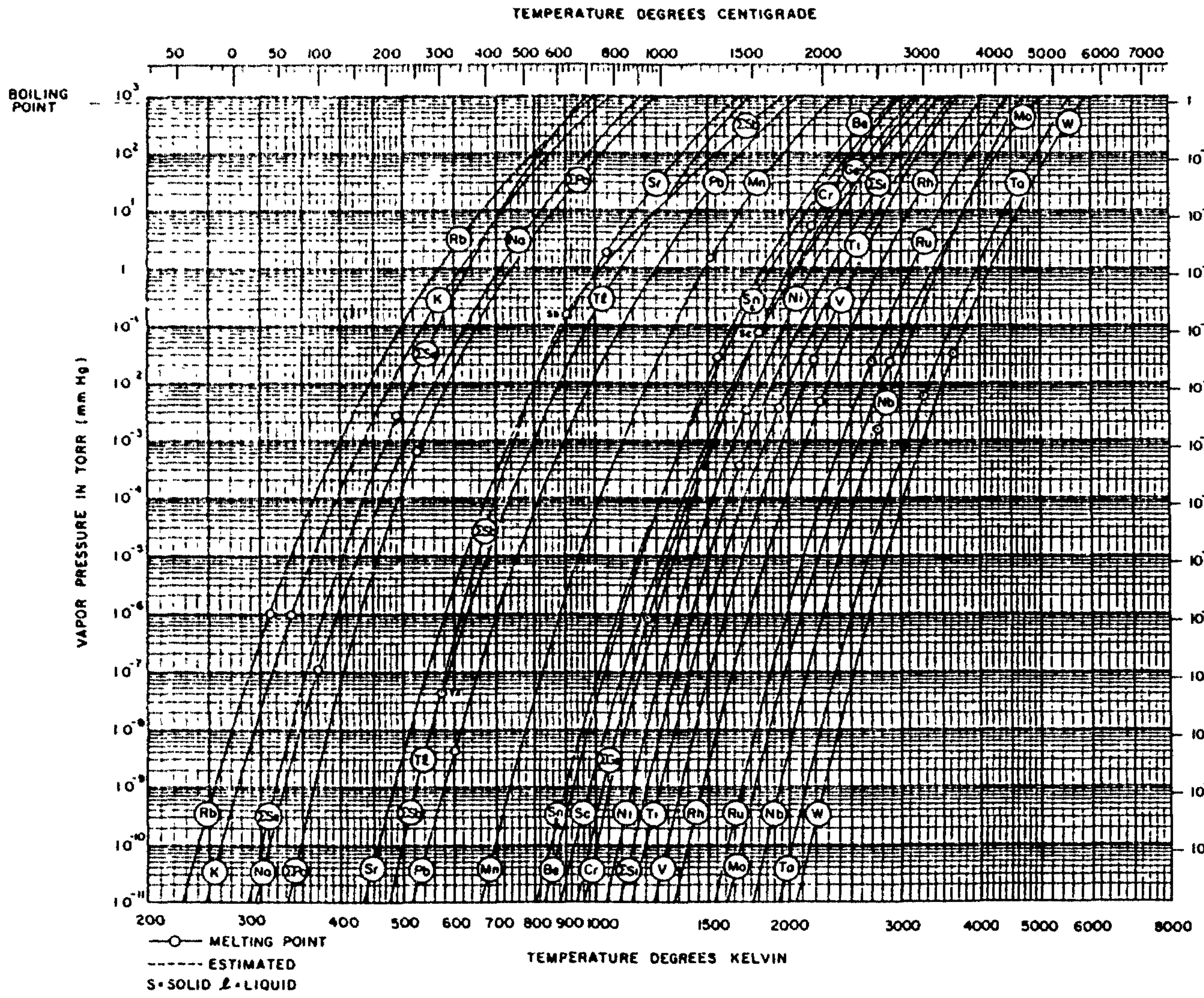


Figure 8 contd. Vapor pressure curves of metals (from "The Characterization of High Temperature Vapors", John L. Margrave, Editor, Appendix A).

powder being placed around it. Preliminary experiments with a 5 kw, 5-8 MHz induction furnace were unsuccessful due to insufficient power; the available power was unable to raise the temperature of either Al or Ni to above its melting point. Consequently, a higher power (40 kw, 5-8 MHz) furnace was used. While the available power was again insufficient for melting and evaporation of both Ni and Al powder, use of $NiCl_2$ powder in place of Ni resulted in ready dissociation of the chloride; the difficulty to melt Al is presumably due to the tenacious layer of oxide around the powder which increases the surface tension of the molten Al. Also, while the use of a solid rod piece of Al at the center did exhibit melting, the melting was only partial, with the Al rod forming a glob at the tip of the rod preventing further melting, presumably due to the reaction of Al with Ni thereby forming NiAl on the molten surface which prevented further melting. Hence, this approach to gas phase plasma reaction did not yield the desired results and was discarded.

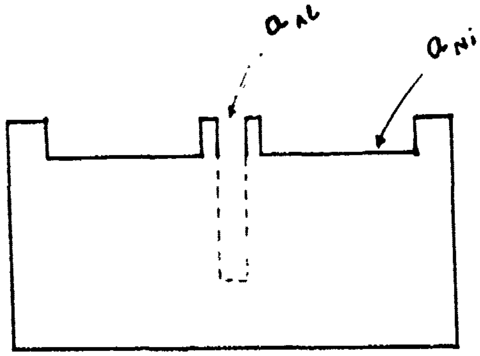


Figure 9. Schematic design of crucible to compensate for the differences in evaporation rates of Ni and Al at any given temperature.

The alternate approach of directly reacting a powdered mixture of $NiCl_2$ and Al in the plasma proved more successful. Preliminary attempts at dry mixing Al and $NiCl_2$ followed by reaction in the plasma in the form of a cold pressed pellet (0.5" diameter, pressed at 1 ksi) resulted in violent reaction. Following reaction, the powder was difficult to collect. Hence, a novel arrangement of a crucible within another crucible was designed to ease the process of collection of powder after the reaction. Figure 10 is a schematic diagram of the arrangement showing three crucibles; the crucible holding the reaction mixture is covered by a slotted graphite crucible which is designed to allow a controlled release of the gaseous reaction products while retaining the reacted powder within the crucibles. A third inverted crucible provides some weight on the slotted crucible to prevent the escaping gases from dislodging the second crucible while allowing the controlled release of gases.

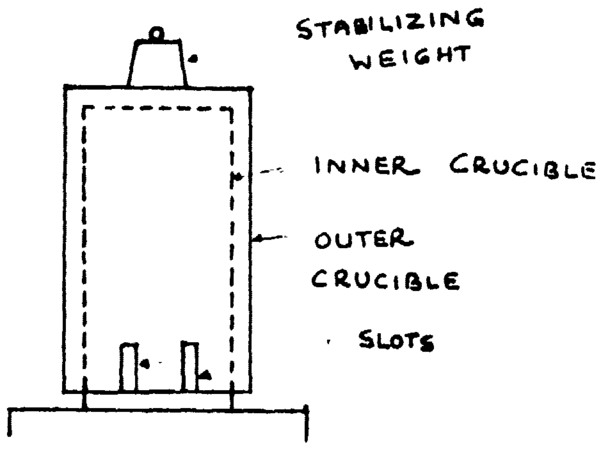


Figure 10. Schematic arrangement of crucibles for gas phase plasma reaction to contain the violent evolution of gases thereby collecting most of the powder within the starting crucible.

X-ray diffraction of the equimolar powder mixture indicated the synthesis of NiAl (see Figure 11), although the intermetallic was contaminated with impurity. Note for example, the peak at 31°, which is the (100) superlattice peak, which indicates an ordered b.c.c (B2) crystal structure which confirms the presence of NiAl. Unfortunately, the peaks at 44.1°, 51.4° etc. do not correspond to NiAl and thus indicate the presence of impurity Ni_3Al. To remove this Ni_3Al impurity, Al-rich powdered mixtures were reacted. The results, however, indicated that the impurity could not be successfully eliminated, see Figure 12, where the NiAl peaks are arrowed. These results are inconsistent with the thermodynamic predictions mentioned above where an Al-enrichment was predicted to enhance the phase stability of NiAl. The discrepancy is probably related to the fact that thermodynamic predictions do not take into account kinetic limitations of a reaction.

B. Plasma Initiated SHS reactions

Although the gas phase plasma reaction failed to produce impurity free NiAl, the plasma initiated SHS reactions, hereafter termed PSHS reactions, proved more successful. PSHS reactions between powders of elementary Ni and Al result in melting, presumably due to the highly exothermic nature of the reaction. The use of a diluent prevents the melting by absorbing a part of the heat generated through the reaction. Preliminary scouting experiments were performed using Al_2O_3 as a diluent. Equimolar mixtures of Ni and Al powder with Al_2O_3 failed to produce impurity free NiAl, see Figure 13 for example. Furthermore, Al_2O_3 was

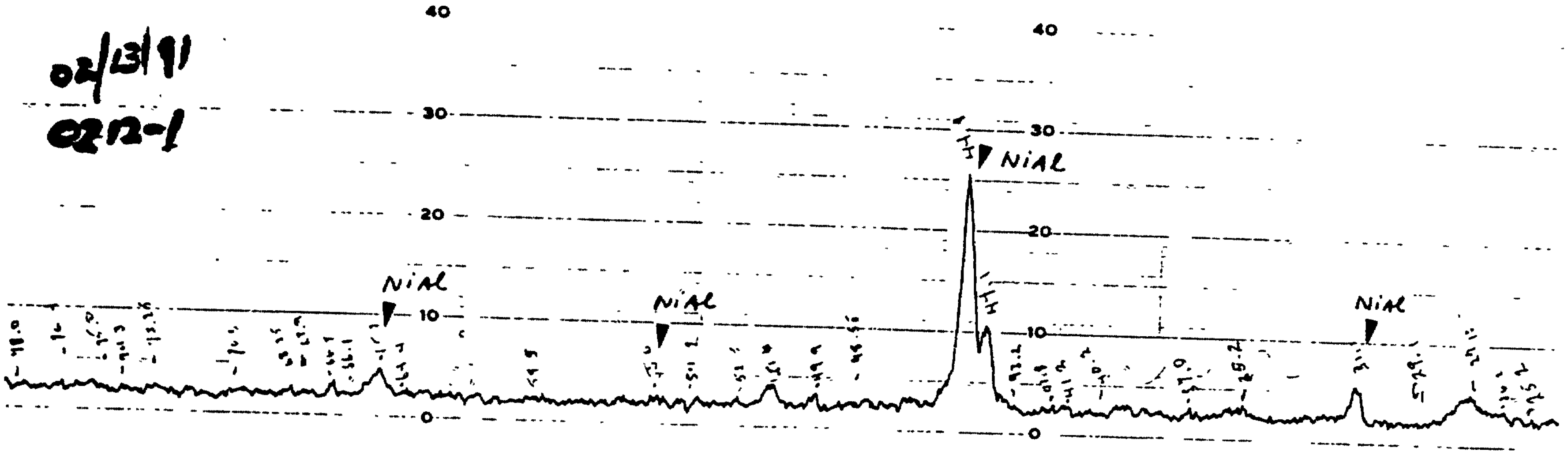


Figure 11. X-ray diffraction pattern of gas phase plasma reacted powder equimolar mixture of Al and $NiCl_2$. The peak at ≈31° is the (100) peak which indicates a B2 (NiAl) structure.

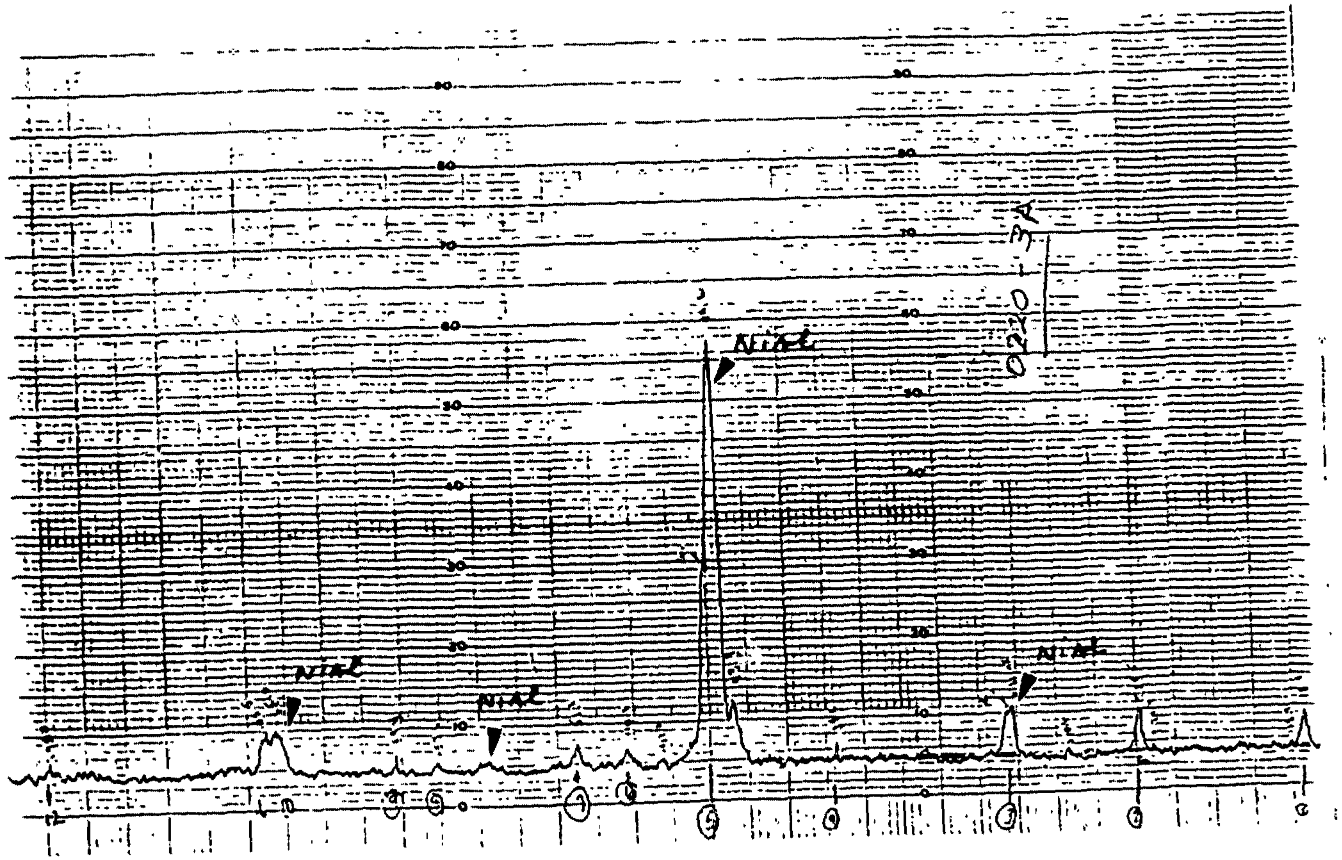


Figure 12. X-ray diffraction pattern of gas phase plasma reacted powder from an Al-rich mixture of Al and $NiCl_2$. The peak at ≈31° is the (100) peak which indicates a B2 (NiAl) structure.

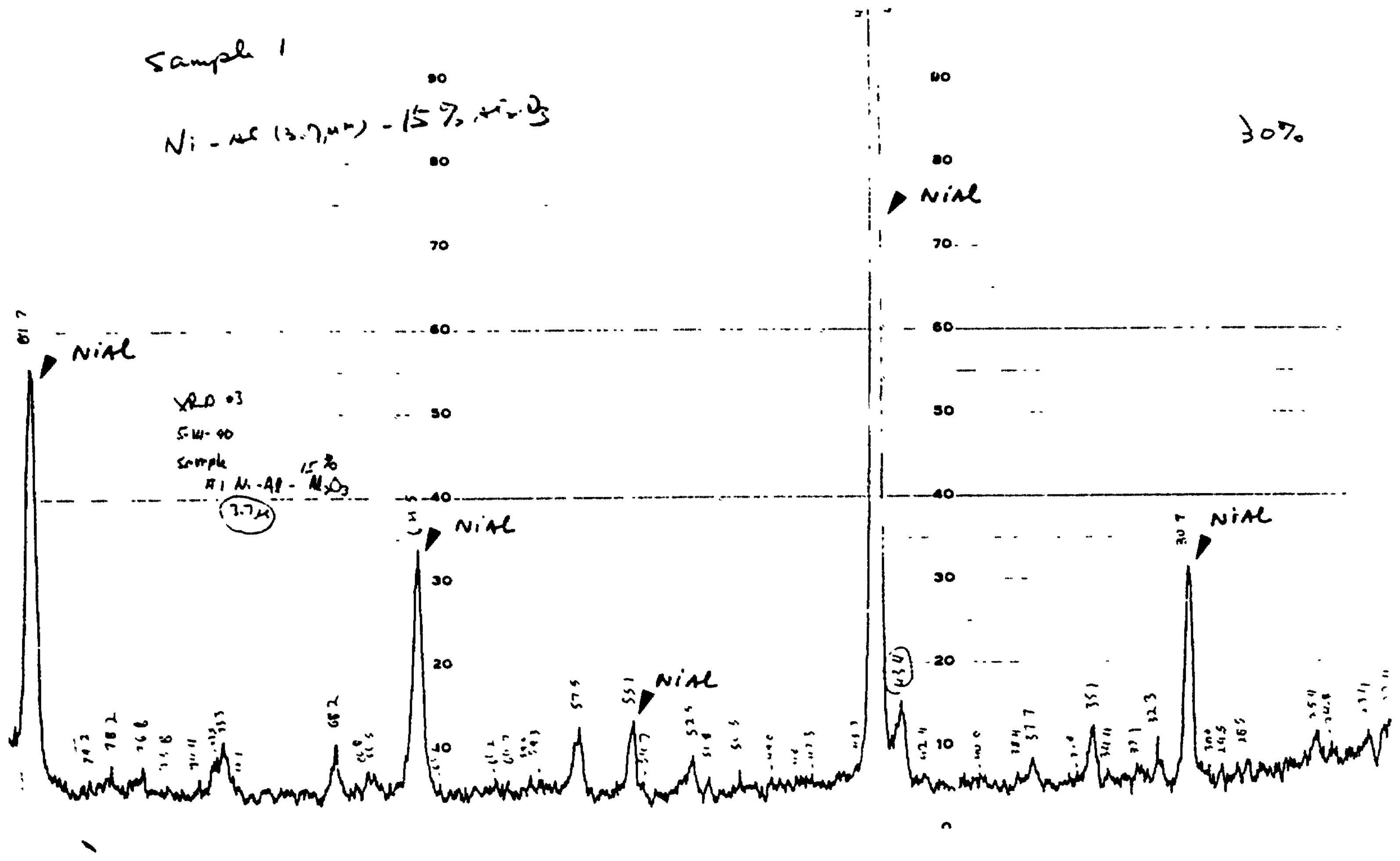


Figure 13. X-ray diffraction pattern of PSHS reacted Ni+Al mixture using Al_2O_3 as a diluent.

not an acceptable diluent in view of the subsequent difficulty in separating the diluent from the reacted intermetallic powder. Hence it was necessary to seek alternative diluents.

Thermodynamic calculations, similar to those described above, indicated that carbon was a suitable diluent. For a stoichiometric reaction mixture (1 mole each of both Ni and Al), it was observed that even for high input carbon concentrations (≈3 moles), no carbide impurities were predicted. It should be noted that the most likely carbide expected is Al_4C_3 since the carbide of Ni is less stable. The stability of solid phases for the above starting stoichiometry are shown below:

Starting stoichiometry: Ni-1 mole; Al-1 mole; C-3.75 mole; Ar-1 mole.

Pressure	**Temp. range**	**Phases**
1 atm	1323-1773°K	C, NiAl, Ar
	>1773°K	C, Ar, Liq. Al
0.5atm	>1773°K	C, Ar, Liq. Al
	1323-1773°K	C, NiAl, Ar
0.1Atm	>1773°K	C, Ar, Liq. Al
	1323-1773°K	C, NiAl, Ar

Starting stoichiometry: Ni-2 moles; Al-3 moles; C-8.75moles; Ar-3 moles.

Pressure	**Temp. range**	**Phases**
1 atm	>1773°K	Liq. Al, C, Ar
	1423-1773°K	C, NiAl, Al_4C_3
	<1373°K	C, Ni_2Al_3
0.5 atm	>1773°K	Liq. Al, C, Ar
	1423-1773°K	C, NiAl, Al_4C_3
	<1373°K	C, Ni_2Al_3
0.1atm	>1773°K	C, Ar, Liq. Al,
	1423-1773°K	C, Ar, NiAl, Al_4C_3
	<1373°K	C, Ar, Ni_2Al_3

Starting stoichiometry: Ni-3 moles; Al-2 moles; C-8.75 moles, Ar-3 moles.

Pressure	**Temp. range**	**Phases**
1 atm	>1773°K	Liq. Al, C, Ar
	1673-1773°K	C, Ni, NiAl
	<1373°K	C, Ni_2Al_3

These results indicate that for small additions of carbon, no contamination is expected. Contamination with Al_4C_3 results only for Al-rich reaction mixtures. Furthermore, Al_4C_3 is unstable especially in the presence of moisture. Also, for the stoichiometric reaction mixture (1 mole of Ni and Al), no carbide contamination is expected. Since equiatomic NiAl compositions are more industrially significant, carbon can be used as a suitable diluent.

Preliminary experiments were performed for three different Al-to-Ni ratios of 1.0, 1.2 and 1.5 while maintaining a constant level (10 wt.%) of carbon as a diluent. The Al powders used for this investigation was ≈1-5μm in size while those of Ni were ≈3μm in size. A small powder size was chosen to achieved better compositional homogeneity of the powder. The powdered mixtures were dry-mixed for 6 hours and pelletized into 0.25" diameter pellets using a pressure of 5ksi. The reacted pellets were ground into powder and examined using x-ray diffraction. The results indicate that, while the stoichiometric (equimolar) and slightly Al-rich (Al-to-Ni of 1.2) compositions were contaminated with impurity phases, the powdered mixture of Al-to-Ni ratio of 1.5 produced impurity free NiAl, see Figure 14. The peak at 25.2° represents graphite. These results were encouraging and were pursued further.

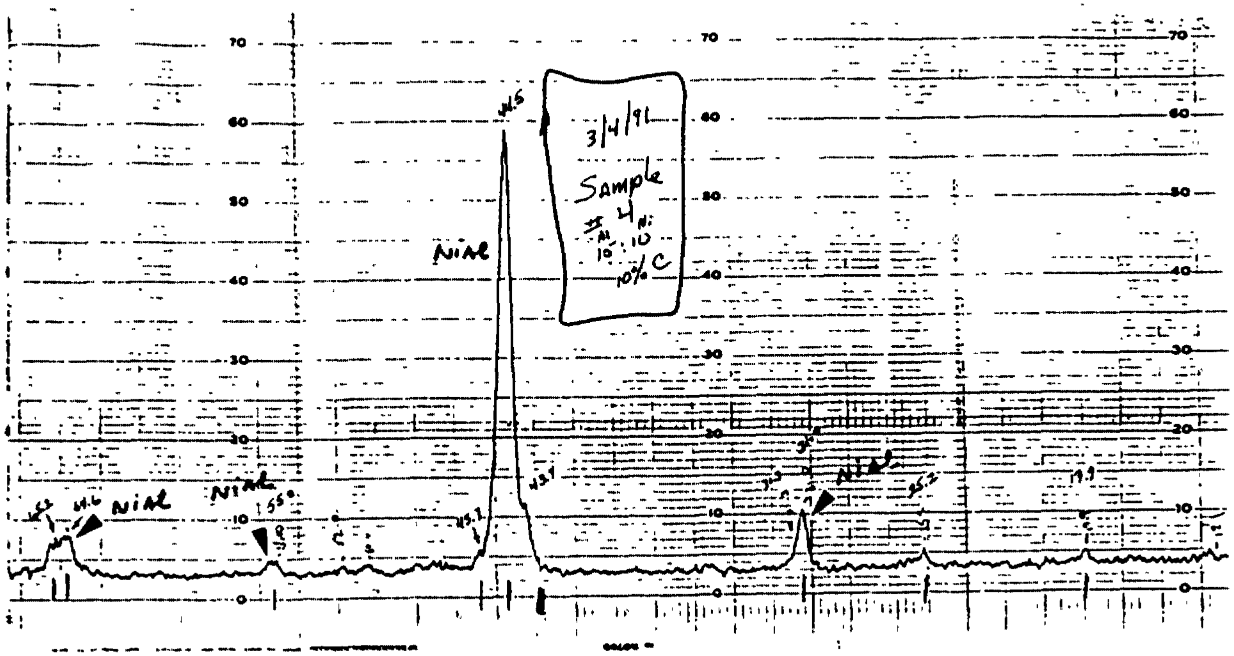


Figure 14. X-ray diffraction pattern of Ni+Al mixture with an Al-to-Ni ratio of 1.5 with 10wt.% carbon added as a diluent. The results indicate an ordered b.c.c (B2) structure free from any major impurity phases.

Interestingly, using a higher diluent content (20wt.%) and a slightly higher pelletizing pressure of 10ksi (the higher pelletizing pressure being necessitated by the higher diluent content), powder mixtures with an Al-to-Ni ratio of 1.2 resulted in impurity free NiAl, see Figure 15a. By contrast, the powder mixture with an Al-to-Ni ratio of 1.5 exhibited impurity phases (see peaks at 48.8°, 52.3° etc. in Figure 15b which do not belong to NiAl). The input power was approximately 1 kw and all the samples reacted within 15-30 seconds. These results indicated that by suitably varying the process variables like diluent content and pelletizing pressures, it may be possible to obtain NiAl powder starting with a powdered mixture of 1:1 (Ni:Al) stoichiometry. This compositional control of the process is critical since NiAl of off-stoichiometric compositions is currently of little industrial interest. The relative importance of pelletizing pressure against higher diluent content in producing impurity free intermetallic compositions was, however, not clear since both the diluent content and pelletizing pressure were varied simultaneously in the above set of experiments.

Interestingly, while impurity free NiAl was produced for starting compositions of Al-to-Ni ratios of 1.5 with 10wt.% C, while those with 20wt.% C resulted in contaminated NiAl, these results indicate that excess diluent may be harmful rather than useful. This was further confirmed by a series of experiments with an Al-to-Ni ratio of 1.0, 1.2 and 1.5 were conducted using a 30wt.% carbon diluent content. Surprisingly, it was discovered that impurity free NiAl could not be obtained in any case. Thus, there

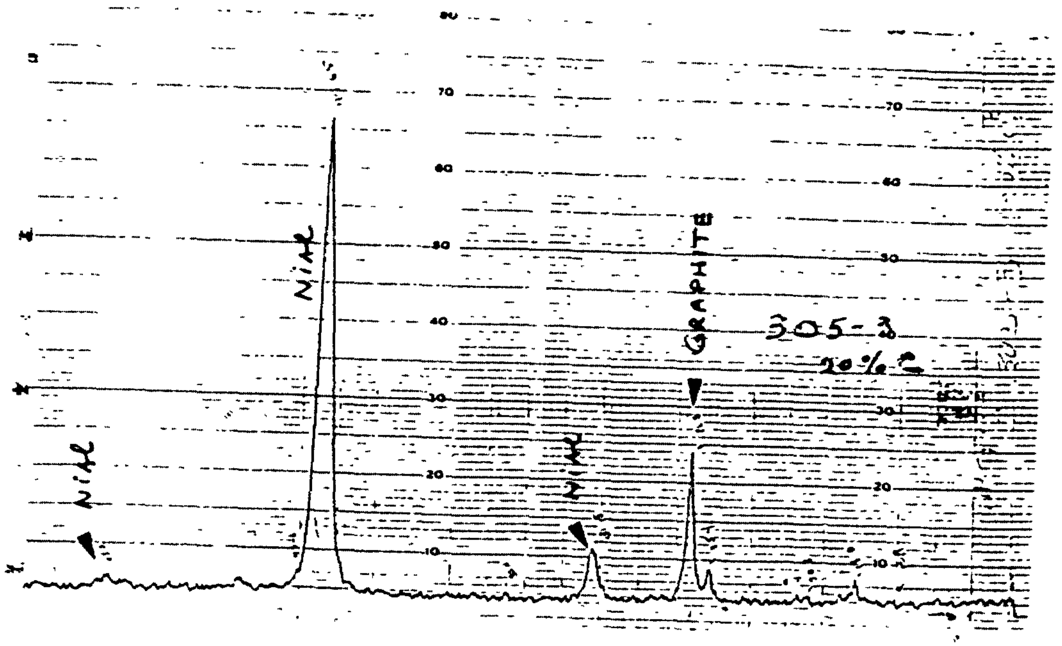


Figure 15a. X-ray diffraction pattern of Ni+Al mixture with an Al-to-Ni ratio of (a) 1.2 (b) 1.5 with 20wt% carbon added as a diluent. For (a), the results indicate impurity free NiAl.

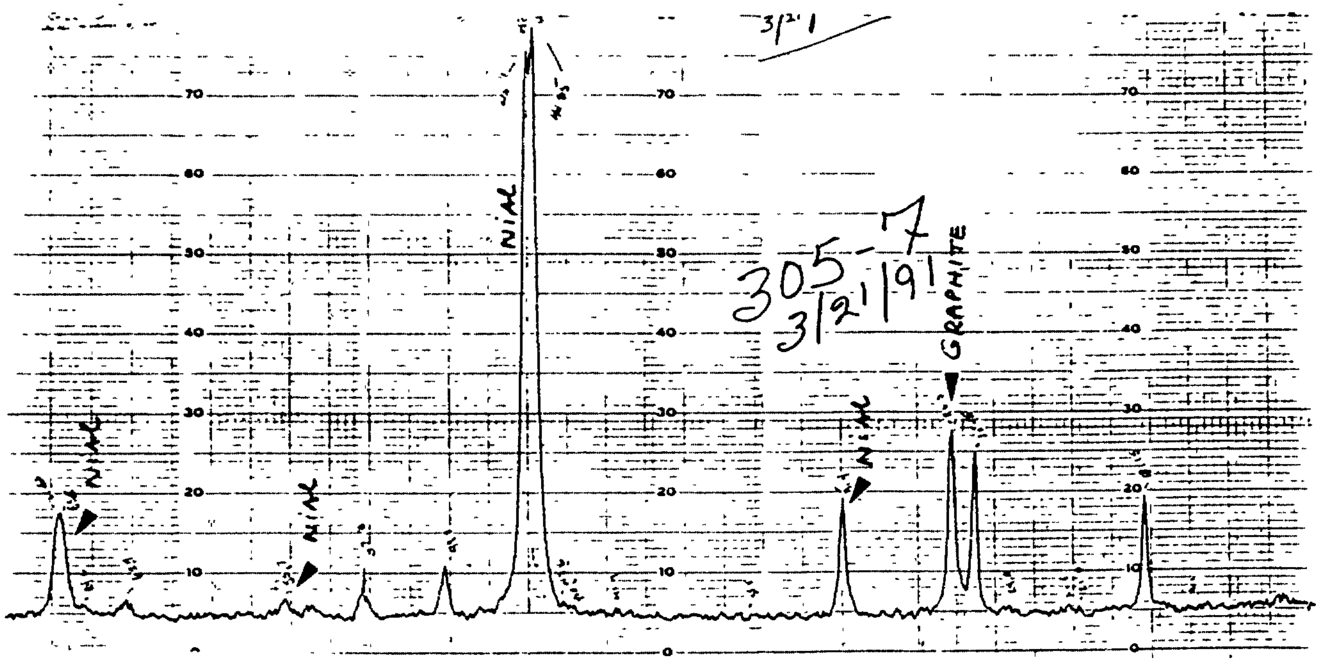


Figure 15b. X-ray diffraction pattern of Ni+Al mixture with an Al-to-Ni ratio of (a) 1.2 (b) 1.5 with 20wt% carbon added as a diluent. For (a), the results indicate impurity free NiAl.

exists some optimum limit to the diluent content, presumably due to excess heat absorption by the diluent leading to insufficient thermal activation for the reaction to be completed.

As mentioned earlier, the relative importance of pelletizing pressure and higher diluent content on compositional control (producing impurity free intermetallic phases) were not clear from previous experimentation. PSHS reacted pellets of Al-to-Ni ratio of 1.2 with 10wt.% C as a diluent were contaminated with impurity phases. Interestingly, pellets of identical composition, and processed identically except for being pelletized at a higher pressure of 15ksi, were reacted in the PSHS process and their powder examined by X-ray diffraction. No impurity phases were observed (see Figure 16) and the results indicate that a higher pelletizing pressure is beneficial to

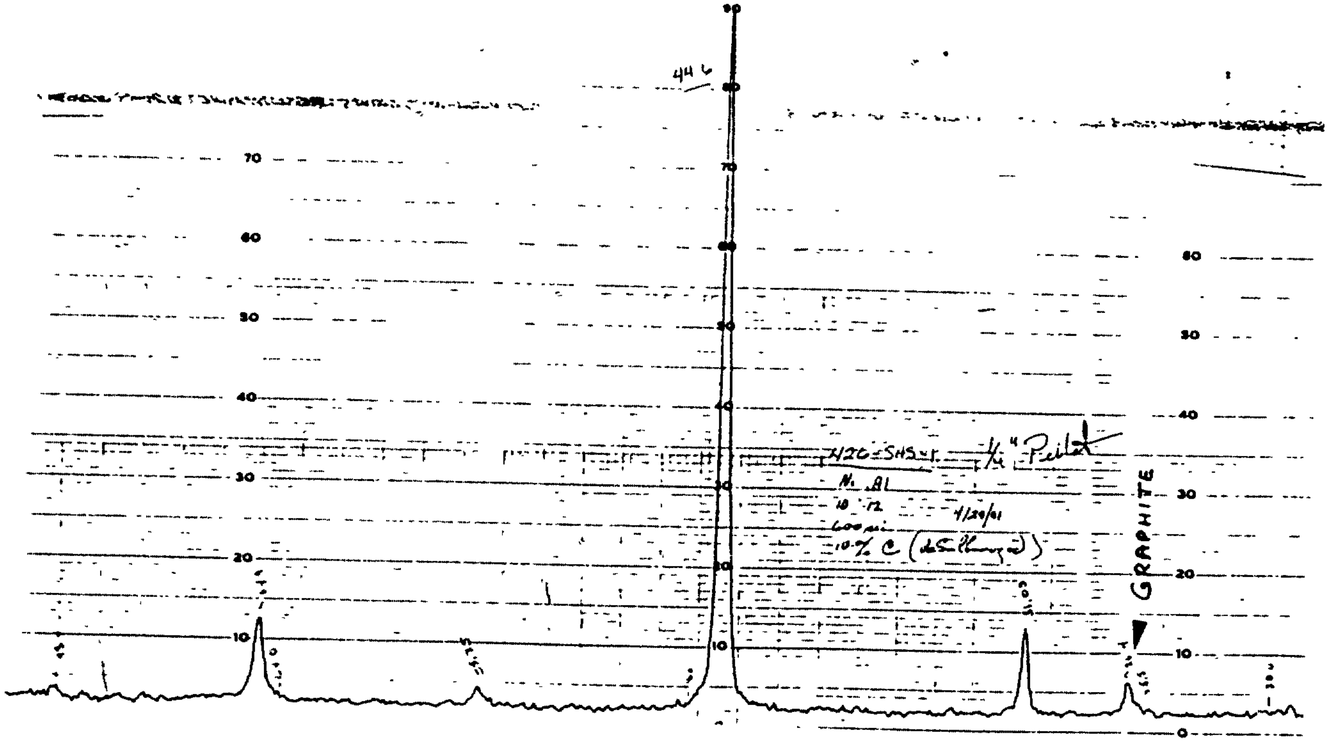


Figure 16. PSHS reacted Ni+Al pellets containing 10wt.%C as a diluent and an Al-to-Ni ratio of 1.2; the pellets were pelletized at 15ksi pressure. Note that the peak at ≈26° represents graphite.

producing intermetallics of controlled composition. The beneficial effect of higher pelletizing pressure is presumably related to enhanced inter-particle contact. The deleterious effect of excess diluent was confirmed by reacting the same molar Al-to-Ni ratio powder with 20wt.% diluent (carbon) under identical conditions where impurity phase Al was observed.

In summary, the above experiments indicated that while some diluent is essential to control the reaction and prevent melting in case of highly exothermic reactions, excess diluent content affects the compositional control adversely. By contrast, the pelletizing pressure has a beneficial effect on compositional control.

Although the above experiments demonstrated that impurity free NiAl could be produced by the PSHS reaction using a suitable combination of diluent and pelletizing pressure, the NiAl compositions produced to this point were off-stoichiometric which presently have less commercial potential than the stoichiometric composition. A series of experiments were performed using an Al-to-Ni ratio of 1.0 and using different diluent contents: 2wt.%, 5 wt.% and 10 wt.%. The pellets were of 0.25" in dimension and cold-pressed at 15ksi pressure. The results were very encouraging. It was observed that, while a 2% diluent content resulted in melting of the pellet, 5% or 10% diluent was adequate to produce impurity free NiAl, see for example Figure 17.

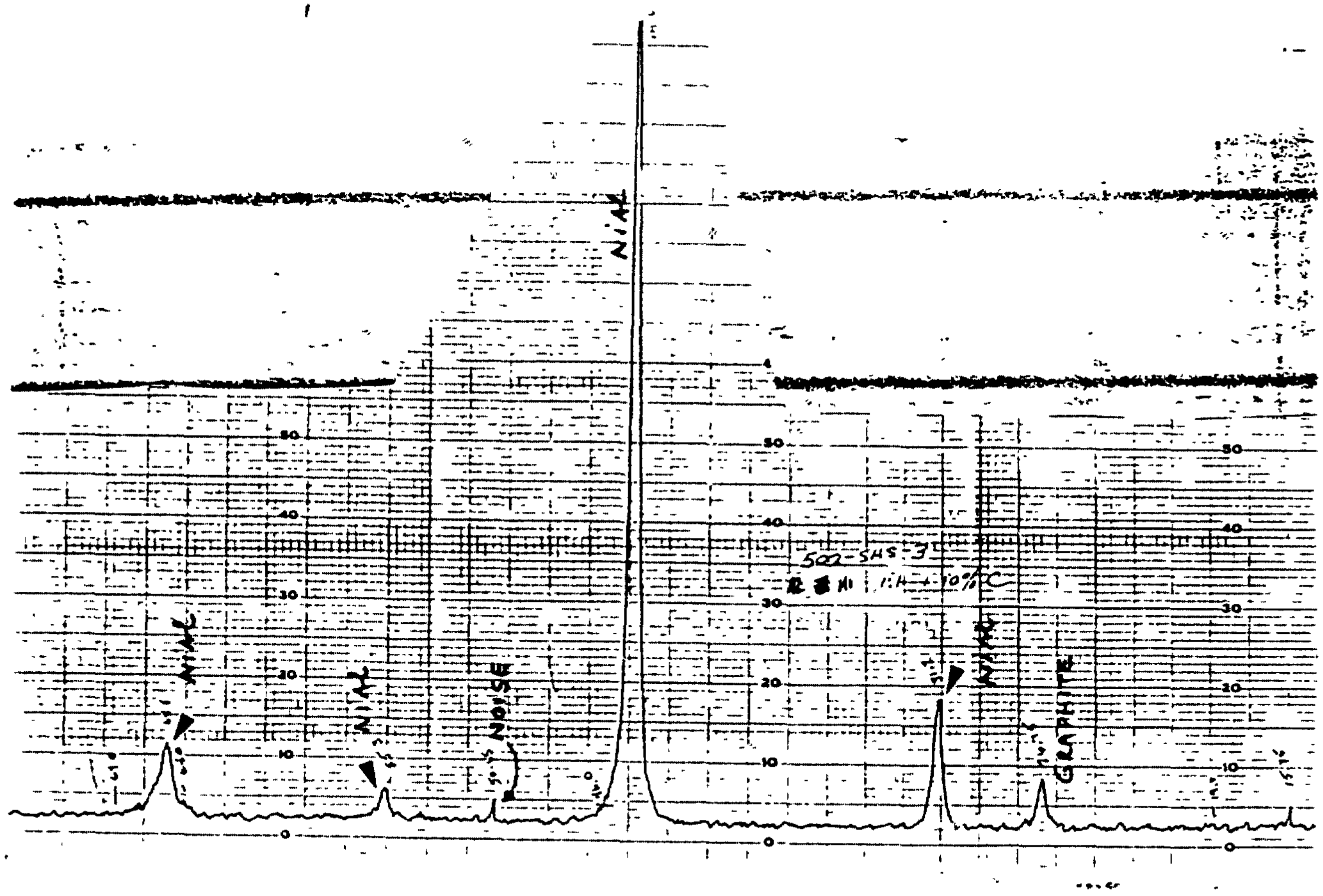


Figure 17. X-ray diffraction of PSHS reacted equimolar NiAl powder (10wt.% diluent content) showing impurity free NiAl. The peak at 50.65° is due to electrical noise and is characterized by a sharp rise in signal strength (unlike regular peaks) and a gradual decay. Again, the peak at 26.45° represents the added diluent.

With the production of impurity free, equimolar NiAl by the PSHS process demonstrated using C as a diluent, the next important objective was to demonstrate the capability of alloying NiAl with a ternary element. Two ternary elements were chosen for this purpose: Fe because isostructural FeAl exhibits complete solid solubility in NiAl and Ti which exhibits extensive (but not 100%) solubility in NiAl. Powdered mixtures of the alloy composition Ni-40at.%Al-30at.%Fe with 10wt.% carbon as a diluent when reacted in the PSHS reactor and examined by x-ray diffraction, exhibited only an ordered b.c.c structure (see Figure 18) which is indicative of the successful alloying of NiAl by Fe.

Similarly, macroalloying NiAl with Ti was performed by reacting powdered composition Ni-48.5at.%Al-3at.%Ti containing 10wt.% carbon as a diluent. Two different pelletizing pressures were utilized: 15 ksi and 25ksi. Examination of the PSHS reacted powders indicated traces of impurity, presumably due to the reaction between Ti and carbon. By contrast, when the powder mixture was reacted without using any diluent, x-ray diffraction indicated that the powder was free from impurity, see Figure 19. Again, the diffractions peaks correspond to an ordered b.c.c structure (NiAl).

These results demonstrate the feasibility of macroalloying NiAl with ternary alloying elements like Fe and Ti using the PSHS process.

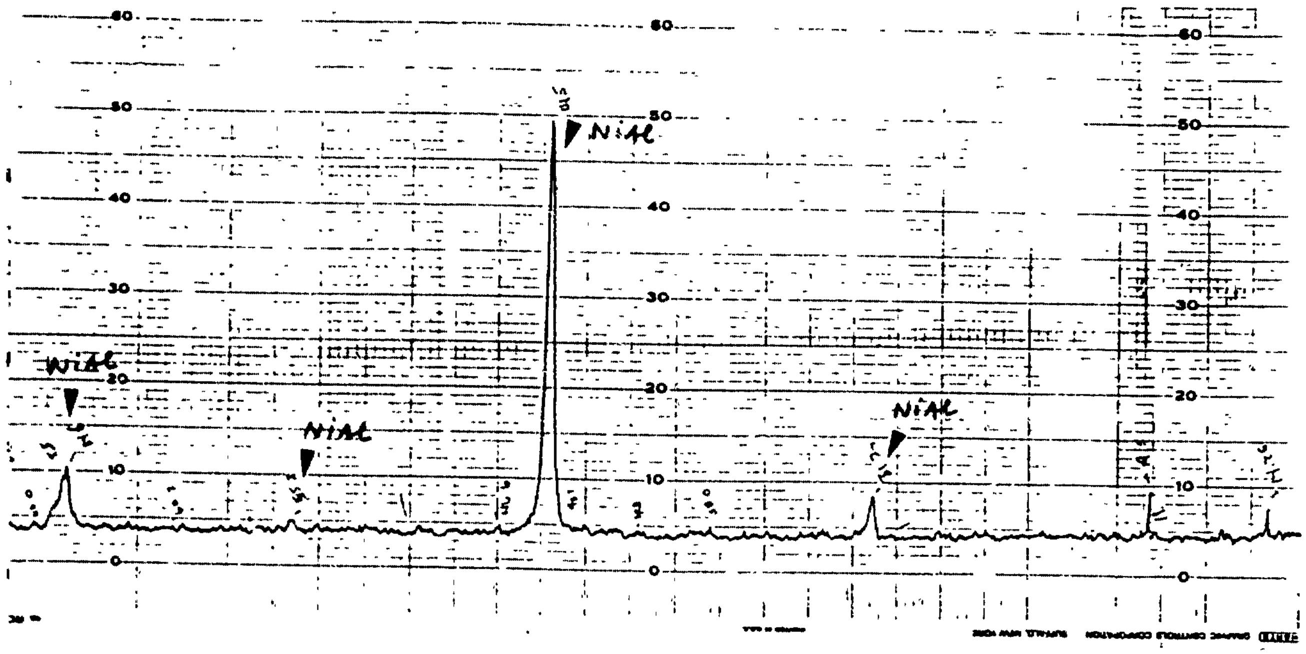


Figure 18. X-ray diffraction of PSHS reacted Ni-40at.%Al-30at.%Fe (10wt.% diluent) powders indicates an ordered b.c.c (B2) structure.

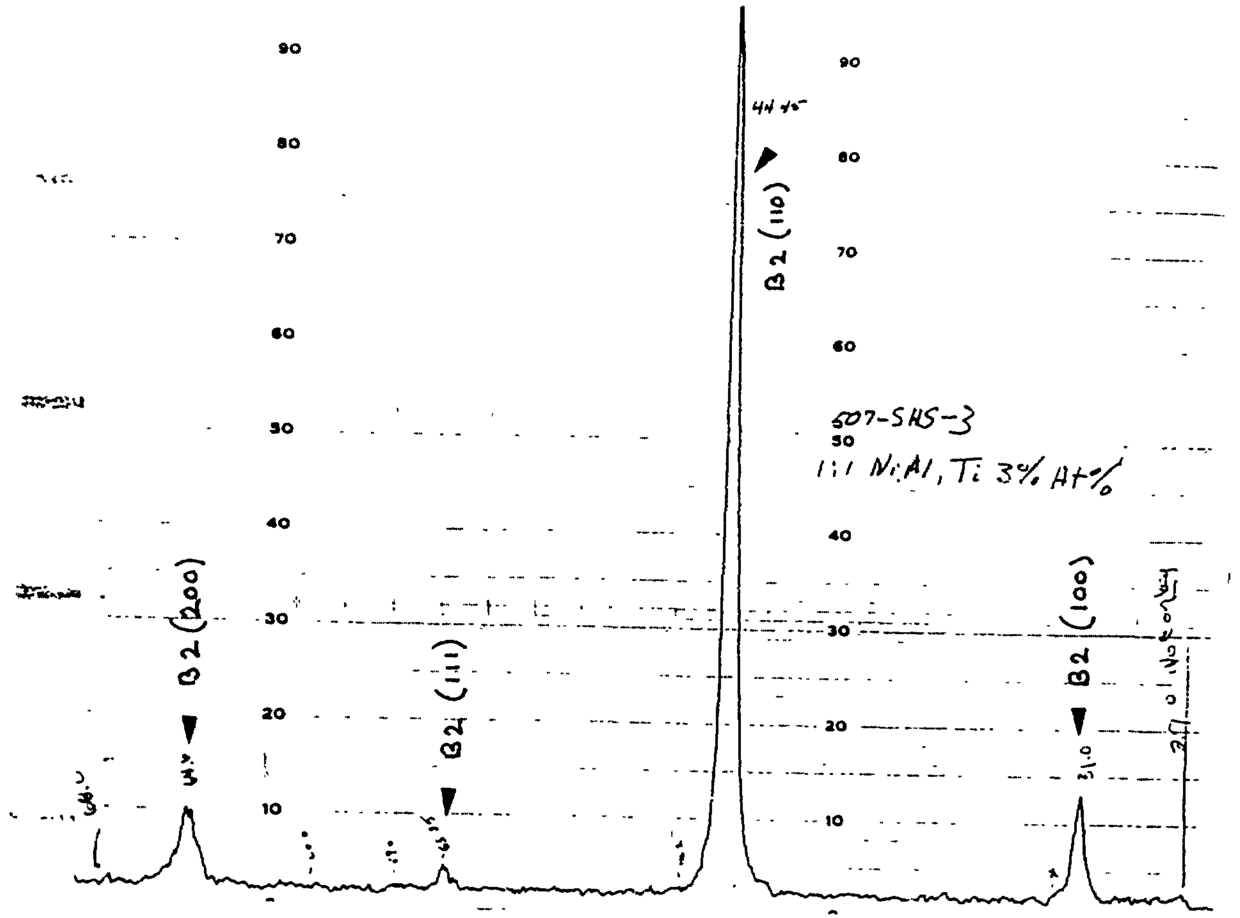


Figure 19. X-ray diffraction of PSHS reacted Ni-48.5at.%Al-3at.%Ti (no diluent) powders indicates an ordered b.c.c (B2) structure.

The final important objective of the program was to produce equimolar NiAl using alternate diluents. While the removal of carbon from powders produced by the heretofore practiced SHS process may be readily achieved by low temperature oxidation (the resulting reducing atmosphere may actually prevent the oxidation of powders), the use of carbon as a diluent is likely to introduce significant quantities of interstitial carbon into NiAl. The effect of such interstitial impurities on the mechanical properties of NiAl are not yet clear. Although the use of Al_2O_3 avoids the introduction of interstitial impurities, subsequent separation of NiAl and Al_2O_3 is difficult. Hence, the most logical approach is the use of the reacted product itself as a diluent to control the reaction. NiAl powders (-80 mesh) were used as a diluent. Fine particled Ni (3 μm size) and Al (1-5μm size) powders were dry-mixed with the following weight fractions of NiAl (-80 mesh) powders: 20, 30, 40 and 50 wt.%. Pellets of 0.25" diameter were cold pressed at 20ksi and reacted in the 8 MHz induction plasma using an input power of ≈4kw. While the pellets reacted well irrespective of the diluent content, those with lower diluent content (20 and 30 wt.%) were easy to de-agglomerate. X-ray diffraction of the reacted powders indicate single phase NiAl for all diluent contents, see for example Figure 20. Hence, it was decided to standardize a 30wt.% NiAl content as a diluent in the production of NiAl powders. Note that this ratio is likely to change for other intermetallics and needs to be determined experimentally.

With the diluent content fixed at 30wt.%, the other two independent variables that determine interparticle contact are the

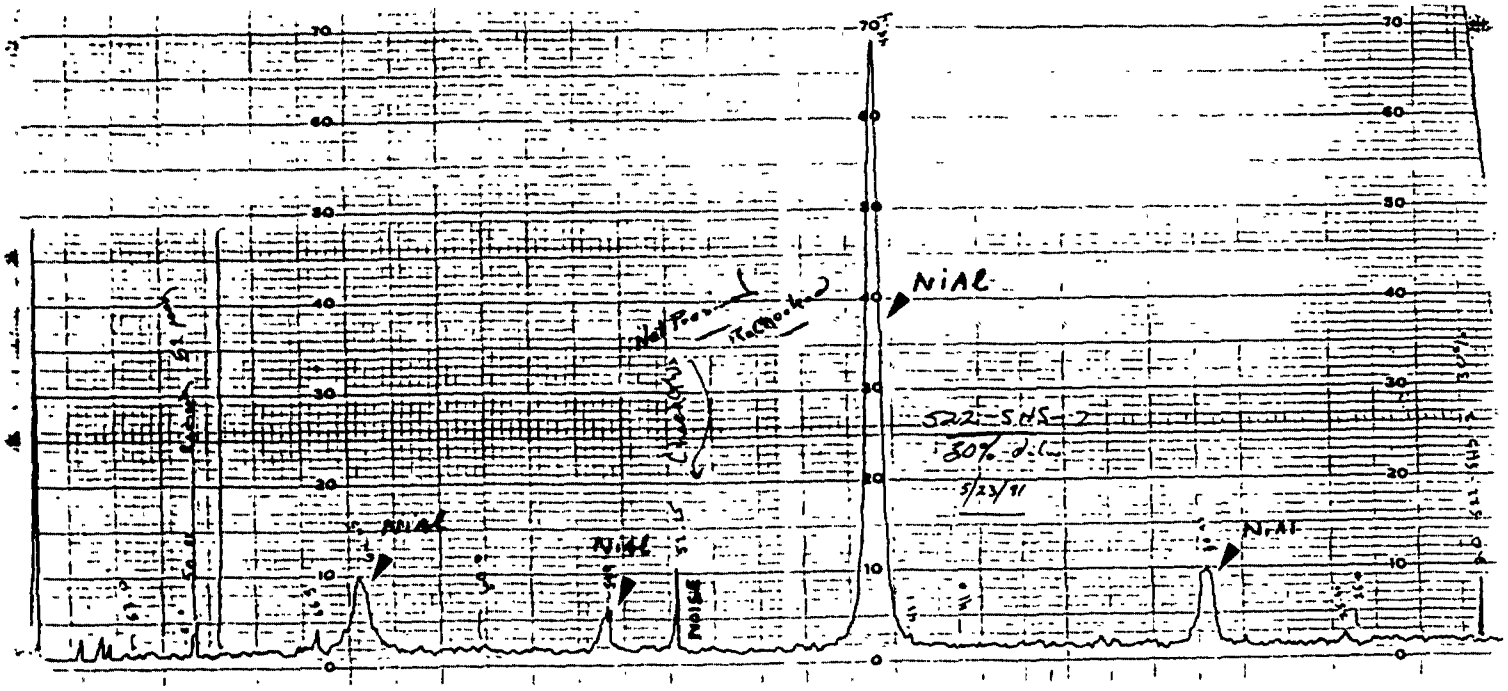


Figure 20. X-ray diffraction pattern of equimolar NiAl powders produced by the PSHS process using previously reacted NiAl powders as the diluent (30 wt.% diluent content). The pattern indicates single phase NiAl, free from any other impurity phases.

pelletizing pressure and the mode of mixing. Pellets of equimolar NiAl of 0.25" in diameter were cold pressed at 10, 15, 20 and 25 ksi. The pellets were reacted using an input power of ≈2.5kw; some melting was observed for higher pelletizing pressures. While a higher pelletizing pressure was generally better from a reaction point of view, the effect of pressure is still under investigation. Similarly, the influence of dispersion mode (wet or dry mixing) and the mixing time (1 to 3 hours) was also determined. Equimolar ratios of Ni and Al powders were wet or dry mixed with 30wt.% NiAl for 1 or 3 hours. Dry mixing was achieved with steel media (a 4-to-1 media-to-powder ratio). Wet mixing was performed in toluene (the hydrocarbon being chosen so as to minimize any tendency of oxidation of Al into Al_2O_3 during the milling process) using a similar charge ratio. The mixed powders were pelletized and reacted using an inductively coupled plasma. The reacted pellets were again deagglomerated and examined using x-ray diffraction. X-ray diffraction analysis indicated single-phase NiAl for all the four processing conditions (see Figures 21a-d) indicating that the dispersion techniques used were adequate to achieve good inter-particle contact. It was noted, however, that wet milled powders were easier to pelletize than dry-milled ones. Subsequently, for NiAl, a processing route of wet milling for 1 hour using a charge ratio of 4 to 1 has been standardized for NiAl.

An additional interesting variable is the effect of pellet size on the purity of powders produced. A 0.5" pellet of wet-milled Ni+Al (1:1 moles) + 30wt.%NiAl powders was reacted using similar power levels (≈2kw) and examined for phase purity. X-ray

Figure 21 a.

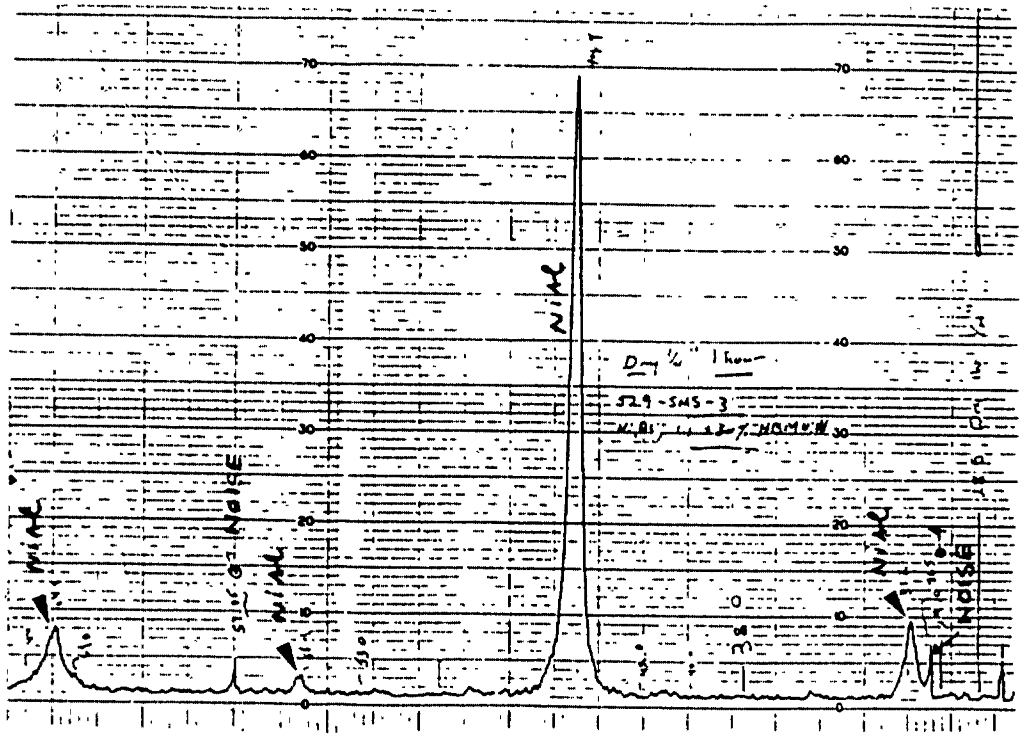


Figure 21. Effect of dispersion conditions on the purity of PSHS reacted NiAl. (a) dry-mixed -1 hour (b) dry-mixed - 3 hours (c) wet-mixed - 1 hour (d) wet-mixed - 3 hours. X-ray diffraction patterns indicate single-phase NiAl for all cases.

Figure 21 b.

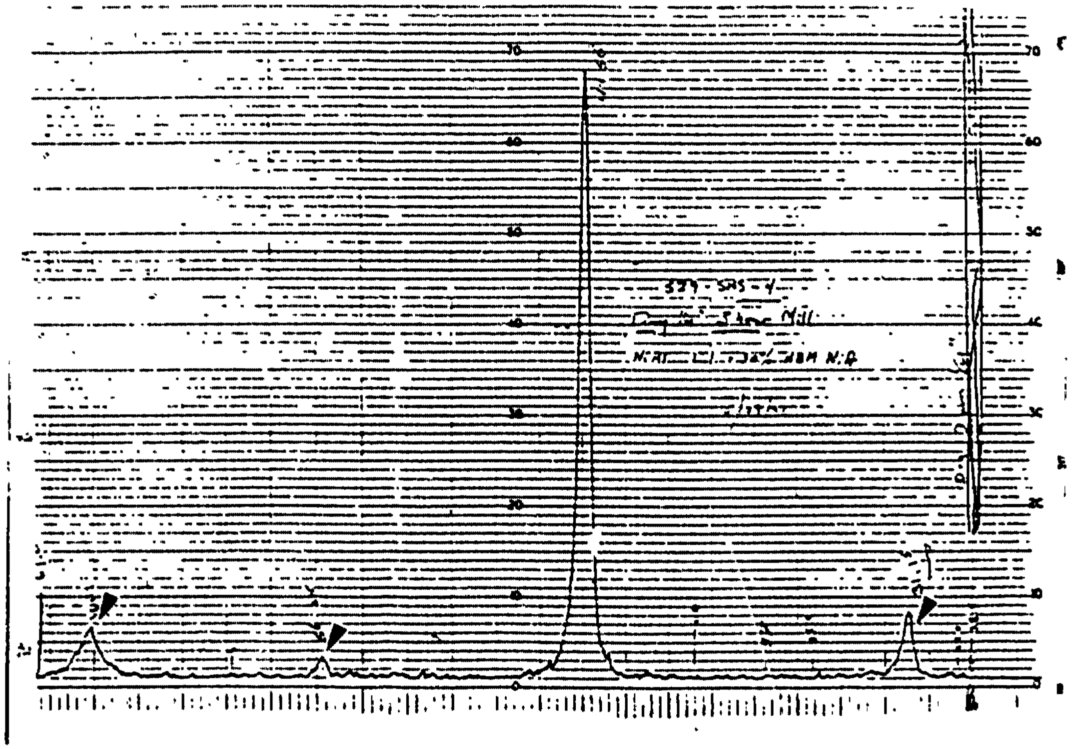


Figure 21. Effect of dispersion conditions on the purity of PSHS reacted NiAl. (a) dry-mixed -1 hour (b) dry-mixed - 3 hours (c) wet-mixed - 1 hour (d) wet-mixed - 3 hours. X-ray diffraction patterns indicate single-phase NiAl for all cases.

Figure 21 c.

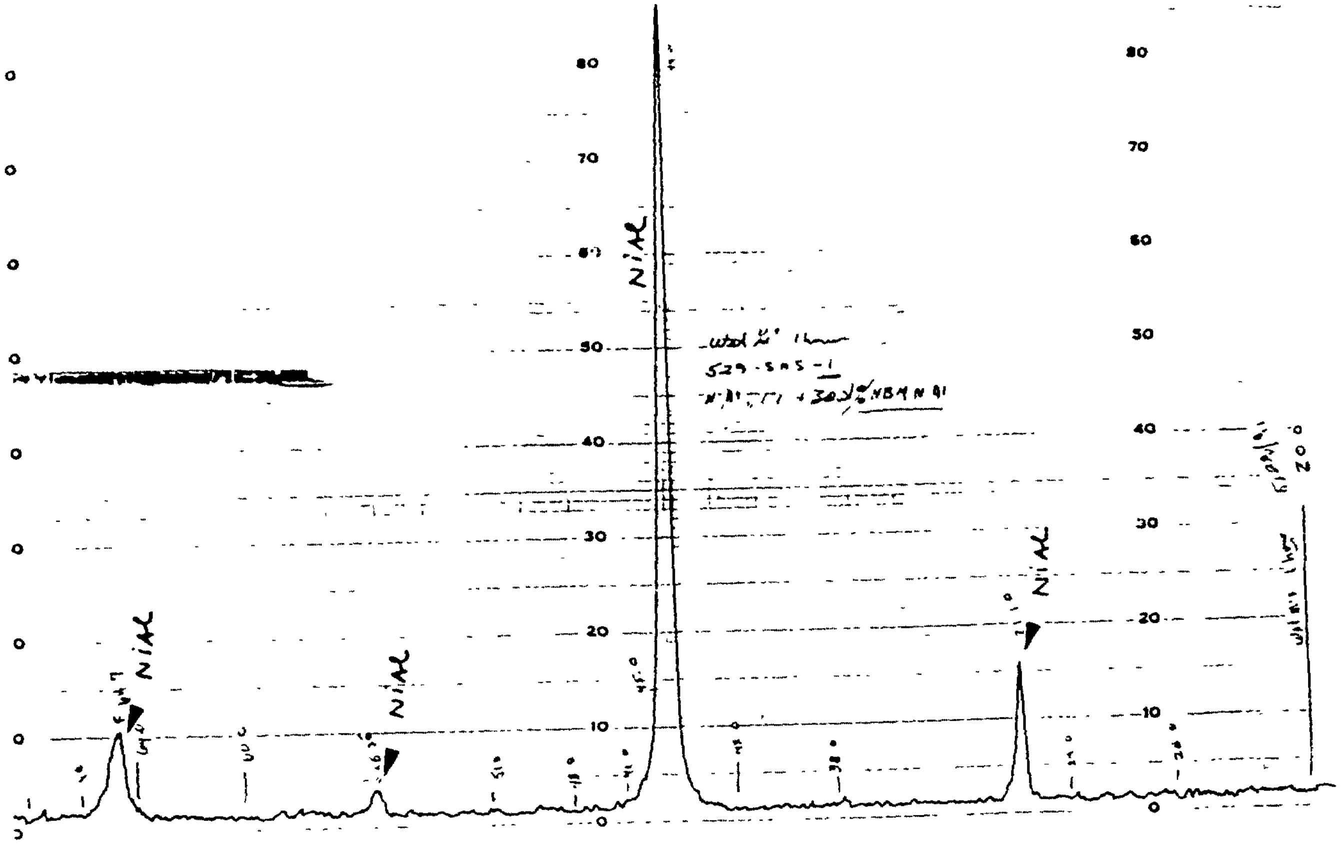


Figure 21. Effect of dispersion conditions on the purity of PSHS reacted NiAl. (a) dry-mixed -1 hour (b) dry-mixed - 3 hours (c) wet-mixed - 1 hour (d) wet-mixed - 3 hours. X-ray diffraction patterns indicate single-phase NiAl for all cases.

Figure 21 d.

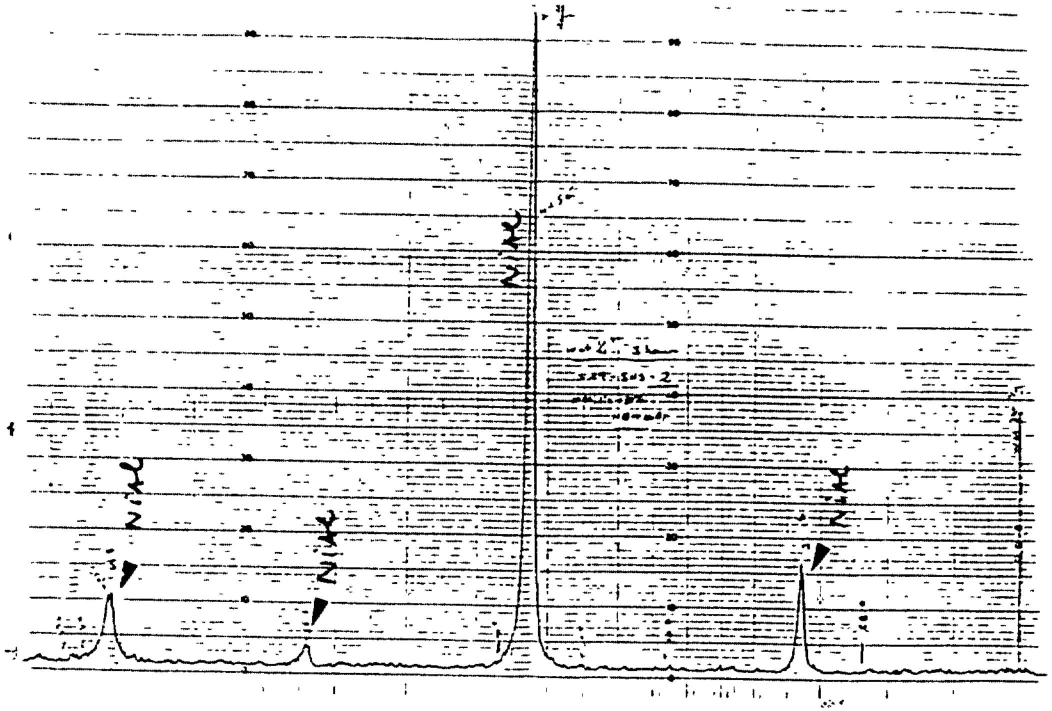


Figure 21. Effect of dispersion conditions on the purity of PSHS reacted NiAl. (a) dry-mixed -1 hour (b) dry-mixed - 3 hours (c) wet-mixed - 1 hour (d) wet-mixed - 3 hours. X-ray diffraction patterns indicate single-phase NiAl for all cases.

diffraction again indicated single-phase NiAl. This observation is important since improvements in rate of production of powders can be achieved only with larger sized pellets.

A small batch (25 grams) of equiatomic NiAl powder was synthesized using the optimized processing conditions and sent to the Army Technical Monitor for independent evaluation. SEM Micrographs, Figure 22, indicate that the particle size was -5μm, although most individual particles were within the 1-2μm range. X-ray diffraction, Figure 23, confirmed the alloy to be single phase NiAl.

C. Pressureless Sintering Experiments

Since the primary rationale behind the use of fine powders is their likelihood of improved sinterability, NiAl powders produced through the PSHS process were cold pressed into a pellet and sintered at 1550°C (near solidus temperatures) for 5 hours. A preliminary investigation into the effect of particle size and pelletizing pressure was also performed.

Two pellets of NiAl, one from fine NiAl powder (see Figure 24a) and the other from an equi-weight mixture of coarse (Figure 24b) and fine powder, were molded at a pressure of 25ksi and pressureless sintered at 1550°C for 5 hours. The pellet synthesized from fine particles was easier to handle than that synthesized from a mixture of coarse and fine powder. Also,

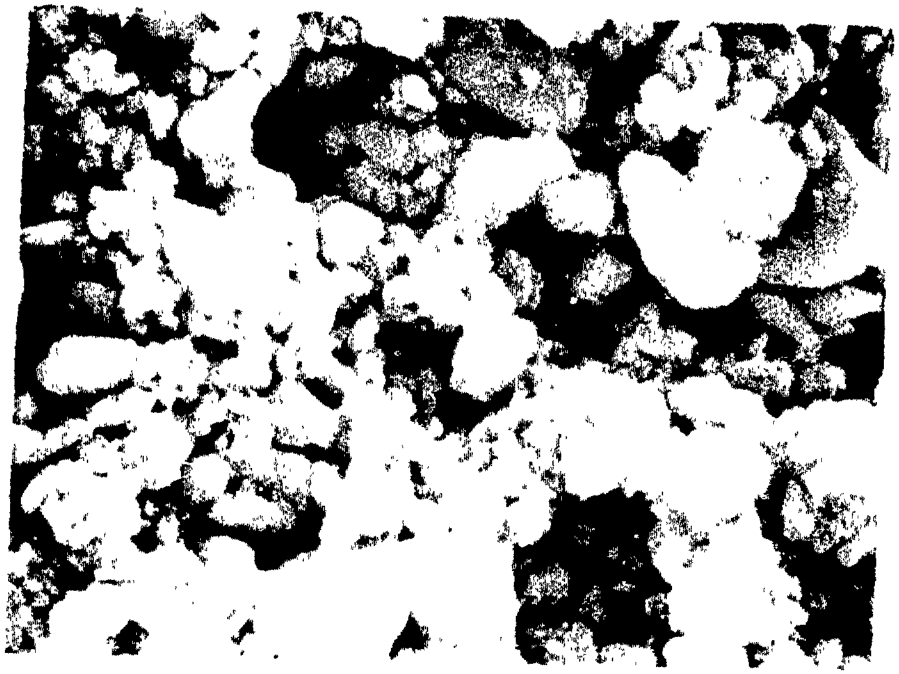


Figure 22. SEM micrograph of equiatomic NiAl powder which was sent to the Army Technical Monitor for independent evaluation. Al particles are less than 5μm in size.

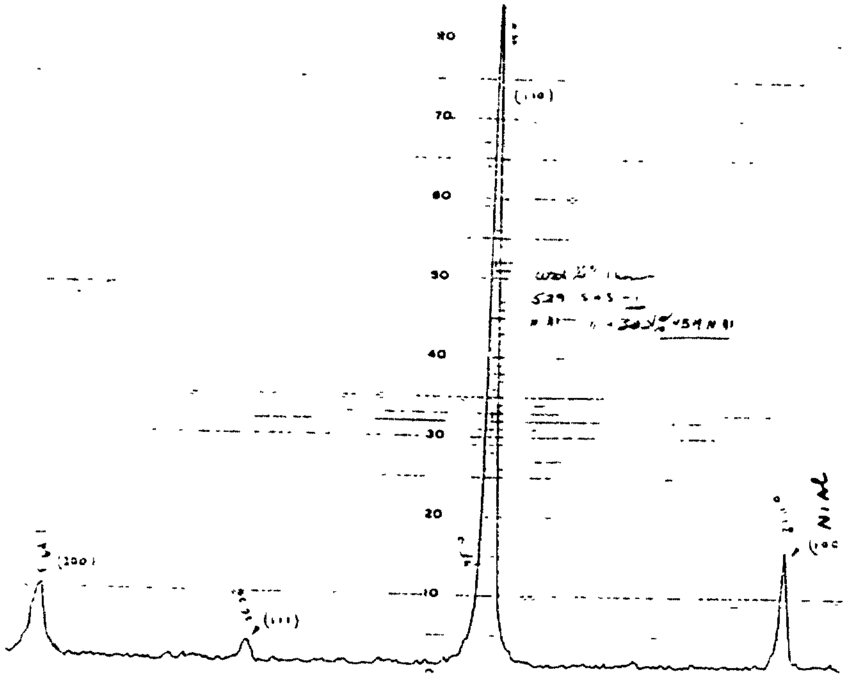


Figure 23. X-ray diffraction pattern from the equiatomic NiAl powder, which was sent to the Technical monitor, indicates only single phase NiAl.

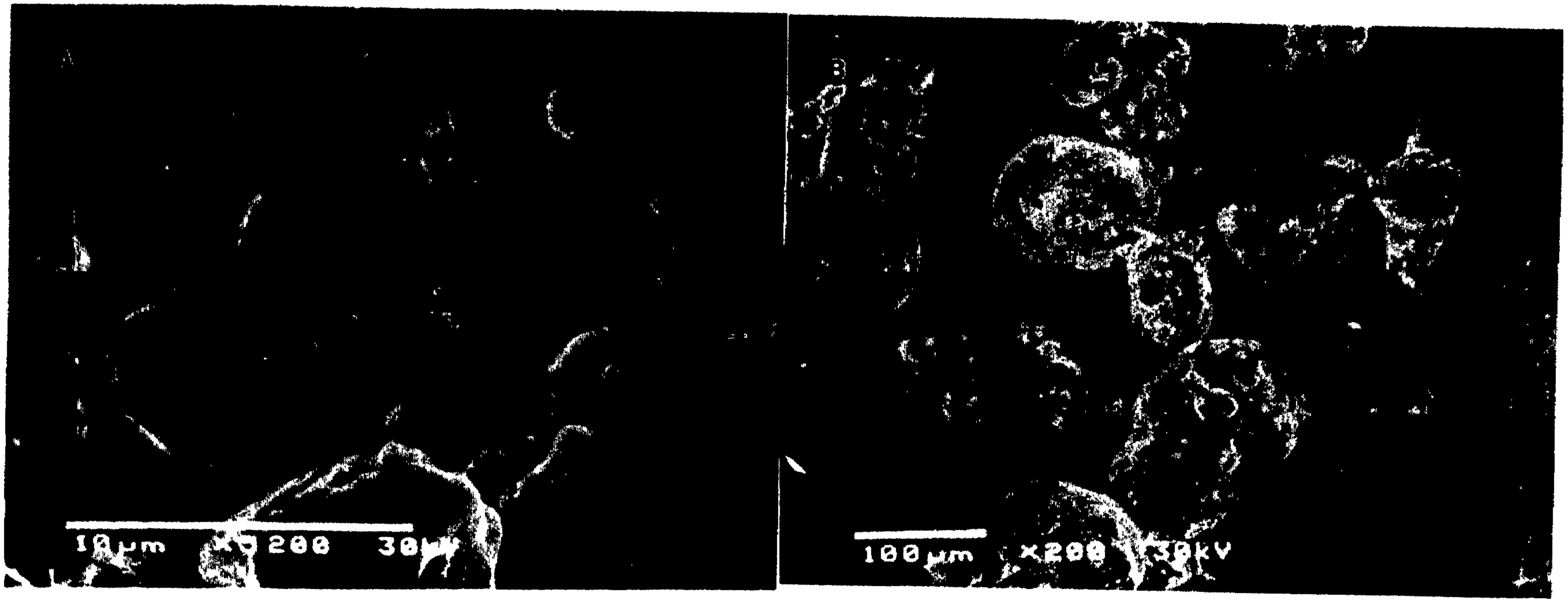


Figure 24. SEM micrographs of (a) fine (≈5µm) and (b) -80 mesh NiAl powders produced by the PSHS reaction.

a cold-pressed pellet made only from coarse powder was impossible to handle and thus not studied. The as-sintered densities of these unoptimized pellets (the density being measured in accordance with the applicable ASTM standard C373) of the former pellet was measured to be greater than 96% of theoretical (5.9 g/cc) while that of the latter to be 88%. Figure 25 is a comparison of the unoptimized processing as-sintered microstructure (secondary electron image) of the two pellets. The larger pores in the pellet of lower density (Figure 25b) emphasizes the advantages of using fine powder in pressureless sintering.

It is thus clear that high densities can be obtained even without optimization for near-net shapes, pressureless-sintered using fine particles; the improved density is likely due to the smaller diffusion distances. The sinterability of the fine powder is also driven by a reduction of the surface energy through reduction of the surface area.

D. Cathode Arc Transport

While the PSHS process was successful in producing fine particles of intermetallic powder relatively economically, the powders were not spherical. Hence, a new process termed Cathode Arc Transport (CAT) was investigated. Like the Gas Phase Plasma reaction discussed earlier, since the intermetallics were to be quenched onto the substrate directly from their gaseous (ionic) state, the resulting particles are expected to be spherical (surface energy arguments). Three alloys were investigated for

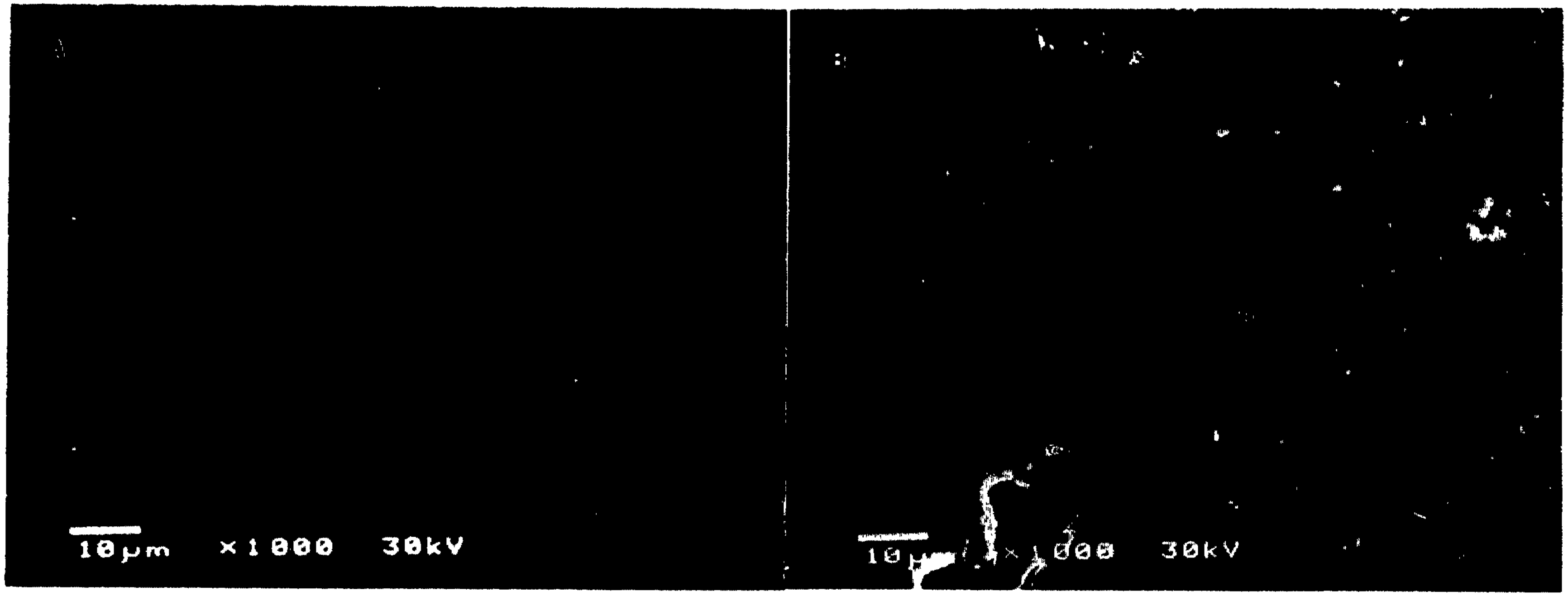


Figure 25. SEM micrographs of pressureless sintered pellets synthesized from (a) fine (<5μm) and (b) equi-weight mixture of coarse (-80 mesh) and fine (<5μm) powder.

this process: Ni-20at.%Al-30at.%Fe, Fe-40at.%Al-1at.%Hf and Ni-50at.%Al. For the alloy Ni-20Al-30Fe, three chamber pressure levels were investigated: 0.1-0.25 mTorr vacuum backfilled to 10 mTorr, 100 Torr and 1 Atm. by bleeding Argon into the chamber. The input power in the three cases were, respectively, 490 watts, 500 watts and 1350 watts. The run times were typically 5-10 minutes. Lower pressures generally yielded very fine powder while a 1 atm chamber pressure resulted in partial melting of the cathode rather than ionization. Figure 26 is a SEM micrograph of Ni-20Al-30Fe particles produced by the CAT process; note that all the particles are spherical and their size typically ranges between 0.1-2μm. Preliminary composition measurements using EDS indicated the successful transfer of Al, Ni and Fe in the powder; no detailed compositional measurements were performed due to their small sizes and lack of standards.

Likewise, spherical powders of the alloy Fe-40at.%Al-1at.%Hf was also produced by evacuating the chamber to a pressure of ≈0.15 mTorr and backfilling it to a pressure of 100 Torr with Argon. The powder was produced using an input power of ≈800 watts. Figure 27a is a SEM micrograph of the powders; note that the powders are also spherical and their typical size is in the range 0.3-1μm, although a few coarse particles ≈2μm in diameter can also be seen. X-ray diffraction from these powders indicated a B2 crystal structure (note the {100} superlattice peak at 2-theta = ≈31°), see Figure 27b. Compositional analysis using EDS again detected the presence of Hf, which was present in only small quantities ≈1at.% in the source cathode rod, in the micron sized powders. This indicates

Figure 26. SEM micrograph of Ni-20at.%Al-30at.%Fe powders produced by the CAT process. The powders are spherical and typically in the size range 0.1 - 2 µm.

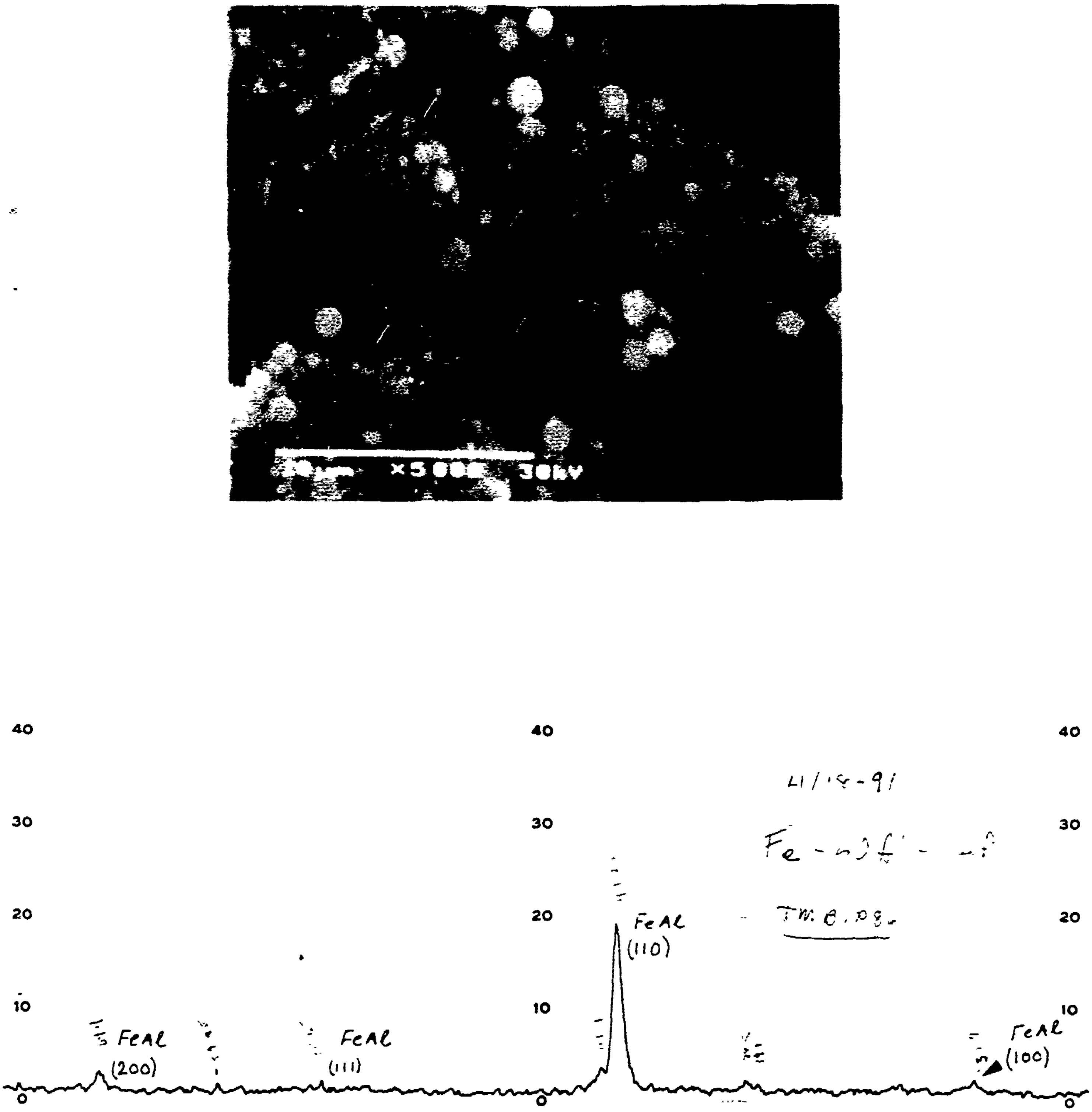


Figure 27. (a) SEM micrograph of Fe-40Al-1Hf powders produced by the PSHS process. The typical powder size is ≈0.5μm although some particles as large as 2μm can also be seen. (b) X-ray diffraction of Fe-40Al-1Hf powders indicate a B2 crystal structure (note the superlattice peaks which are arrowed).

that successful transfer of constituent elements from cathode to the powder was achieved.

And finally, preliminary experiments were performed using a cathode source rod of Ni-50at.%Al (obtained from NASA Lewis Research Center, courtesy of Dr. M.V. Nathal). Like the previous cases, the chamber was evacuated and backfilled to ≈100Torr Argon pressure and the powder generated using an input power of ≈400 watts. Unlike the previous cases, the powder particles in this case were somewhat larger, ≈1-10μm. The limited quantity of powder generated prevented an x-ray diffraction analysis of the powder; EDS measurements, however, confirmed the presence of both Ni and Al in these powders. Figure 28 is a backscattered electron image showing the spherical powders of Ni-50Al produced by the CAT process.

The above results, while promising, also indicate that an optimization of process parameters, especially input power and chamber pressure, are necessary to reliably produce spherical intermetallic powders in a controlled sub-micron to micron size range.

VI. DISCUSSION

Booth [35] was the first to lay the mathematical foundation for what has since been referred to as self-propagating high temperature synthesis (SHS), where, once initiated, the strongly exothermic reactions are known to sustain themselves and propagate

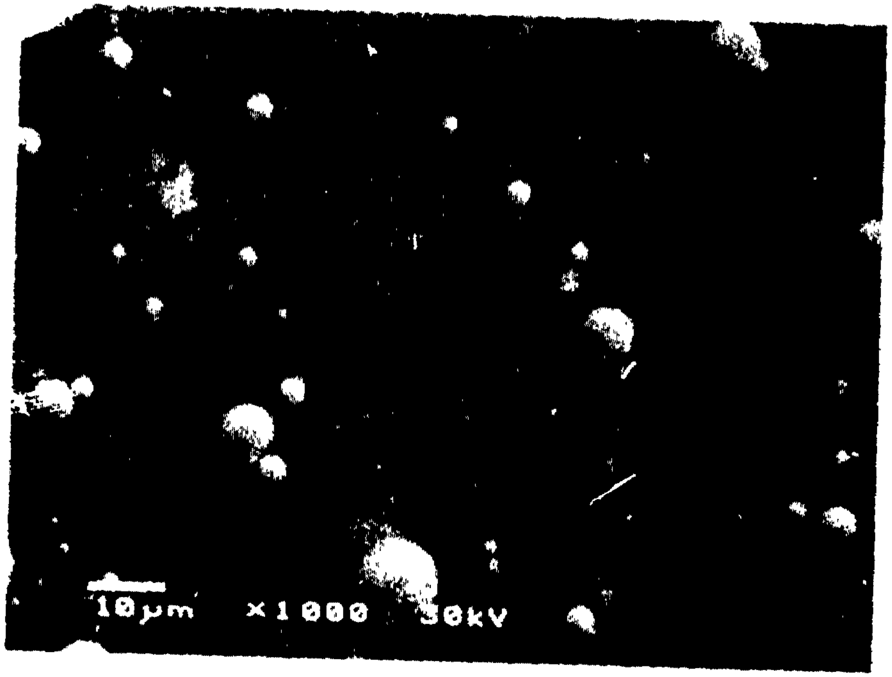


Figure 28. SEM backscattered electron micrographs of Ni-50Al powders produced by the CAT process. The powders are coarser (in the size range 2-10μm) than those produced for other alloys.

in the form of a wave until the reactants are completely consumed. Many investigators have reported on the different aspects of the SHS process. Among the various phases investigated, the aluminides have received considerable attention. These include aluminides of nickel [36-42], niobium [43], zirconium [44], Iron [45] etc.

The Ni-Al binary system contains four intermetallic compounds (in increasing order of Ni content): Al_3Ni, Al_3Ni_2, AlNi and $AlNi_3$. The equiatomic phase, NiAl, has the highest heat of formation, -58.79 $kJmol^{-1}$, the highest melting point, 1911°K, and also a high adiabatic temperature of 1923°K [40]. Thus, in theory, the reaction product will be a liquid phase. Experimentally, equimolar powder mixtures of NiAl indeed exhibit melting resulting in a cast product.

Philpot et al.[46] studied the mechanism of formation of Ni_3Al from a powder mixture of Ni and Al using SHS reactions. The effect of three process variables namely the aluminum concentration, heating rate and nickel particle size on the initiation temperatures, temperature rise and density of final product was studied. For an aluminum content up to 25 at.% Al, lower heating rates (1-2°K/min) resulted in two peaks; slightly higher heating rates (5°K/min) resulted in a single peak. For higher aluminum content (30 at.%), only a single peak was observed irrespective of the heating rate. For reactions which exhibited two peaks, the first peak was attributed to heat generated as a result of solid state reactions while the second peak was related to the reaction between liquid phases (mainly aluminum) and nickel. Also, the highest temperature of the first peak was observed to be lower than the initiation temperature of the second peak, indicating that the heat generated by the solid state reactions was sufficiently high to initiate the second liquid-solid reactions. The present investigation, however, did not aim at determining the phases formed along the reaction path, rather, unlike previous investigations, the emphasis was to produce impurity free intermetallic NiAl. The temperature of the pellet could not be monitored as a function of the heating time since the inductive field interferes with the millivolt level signals from the thermocouples. Furthermore, our manually operated optical pyrometer was too slow to determine temperatures just before and after the reaction. Visual observations, however, indicated the occurrence of only one reaction peak; the pellets were typically dull red-hot (500-800°C approx.) before and just after the reaction and almost white-hot (≈1500°C or above) during the reaction.

Increasing aluminum contents or the heating rates resulted in an increased onset temperature T_i (reaction initiation temperature) and also an increased ΔT (temperature rise following reaction). Similarly, decreased Ni particle sizes resulted in an increased reaction onset temperature T_i and increased temperature rise ΔT. This is the principal reason for using fine (3μm) nickel powder in the present investigation. Furthermore, the initiation of the reaction in the present investigation by inductively coupled plasma provides high heating rates, well in excess (≈1000°K/min instead of 10-50°K/min) of those studied by all previous investigations. The positive dependence of ΔT on the aluminum concentration and negative dependence on nickel particle sizes are related to enhanced aluminum-nickel contact. The dependence of T_i on heating rate is related to a change in the reaction mechanisms from initial solid state reaction (where two peaks are observed) for slower heating rates to the liquid-solid interactions (single peak reactions) for higher heating rates. The dependence of ΔT on heating rates is related to the compositions at different stages of the reaction; at slower heating rates where some Al is consumed by solid state reactions, subsequent reactions between the remaining aluminum (liquid), nickel and the solid reaction products (intermediate intermetallics, see below) results in reduced magnitude of heat generation than the case (high heating rates) where no solid state reaction occurs, and hence, a larger quantity of liquid aluminum is available for reaction directly with nickel (which releases more heat than reaction with intermediate intermetallics). While the previous investigations were performed using furnace heating/ignition coil to initiate the reactions, the heating rates in the inductively coupled plasma being several orders of magnitude greater than the former two, the resulting high T_i and ΔT led to initiation of reaction instantaneously throughout the whole pellet (reaction time for the whole pellet being less than 1 second).

At slower heating rates, the reaction path in the formation of the desired intermetallic Ni_3Al has been outlined by Philpot et al.[46] (starting powder mixture composition of Ni-17.5at.%Al) with the aid of microscopy and x-ray diffraction. Since slower heating rates result in two peaks, the phase distribution before and after both peaks was analyzed by x-ray diffraction. It was observed that initial heating results in the formation of minor volume fractions of intermetallics Al_3Ni and some Al_3Ni_2, presumably by solid state diffusion. Further heating resulted in Al_3Ni_2 from direct reaction between nickel and Al_3Ni or Al. No Al_3Ni peaks were detected at this stage and Al and Ni continued to be the major phases. Further heating to a temperature just before the initiation of the second peak resulted in $AlNi_3$ as the major compound (note that nickel also continues to be the major phase) although other intermetallics like Al_3Ni_2 and AlNi could also be detected. Finally, after the second peak, the primary intermetallic phase was $AlNi_3$ although minor fractions of AlNi and Al_3Ni_2 were still present. Under these conditions, all the aluminum was consumed and substantial amount of nickel remained unreacted. The excess nickel was not surprising in view of the starting stoichiometry since a $Ni+AlNi_3$ microstructure is expected for a starting composition of Ni-17.5at.%Al even after complete reaction. Interestingly, for higher (2-5°K/min) heating rates, the fraction of desired intermetallic phase was similar in all cases. The above discussion indicates that for slower heating rates, the reaction initiates from the aluminum rich end of the phase diagram and all the intermediate Al-rich phases are formed before the intermetallic corresponding to nominal powder stoichiometry is produced. Unfortunately, it also indicates the potential for contamination of the desired intermetallic by other phases. Fortunately, the present investigation demonstrates that using a suitable combination of reactant particle size, pelletizing pressure and heating rates, single phase intermetallics of stoichiometry corresponding to the nominal powder mixture stoichiometry can be produced free from any other intermetallic phases or unreacted constituent species.

In contrast to the case described above, for mixtures containing higher aluminum contents (25at.%Al), a higher heating rate resulted in a higher volume fraction of the Ni_3Al phase. Since this reaction occurs only by a single peak, the higher volume fraction of Ni_3Al for Ni-25at.%Al mixture than Ni-17.5at.%Al mixture indicates that not only is the amount of aluminum important (the formation of product phase is limited by the available aluminum), but also that the amount of products formed are probably also related to the thermal history of the sample (any solid state reactions which may deplete available aluminum content) prior to combustion. Fortunately, for reactions initiated in an inductively coupled plasma, solid state reactions are of a lesser concern and, by virtue of its high heating rate, the process is capable of permitting only liquid-solid reactions which should lead to better product purity.

Finally, for a given composition, a higher heating rate resulted in a reduced porosity content, presumably due to the larger available liquid aluminum phase during higher heating rates; the presence of a liquid phase in powder compacts can lead to a decrease in porosity through re-arrangement or sintering. This observation is consistent with those by several others who attempted to produce fully densified bodies through the SHS reactions. By contrast, since the aim of the present investigation was to produce powders, the goal was a porous reacted mass.

While Philpot et al.[46] have examined the reaction mechanism in the synthesis of Ni_3Al through SHS, German et al.[47] have also examined the effect of some other processing variables like stoichiometry, milling time, heating rate, aluminum particle size and reaction atmosphere. Unlike Philpot et al.[46], however, German et al.[47] were primarily concerned with reducing the porosity content of the reacted material so as to obtain near-net shapes. They reported a stoichiometry of 86.7wt.%Ni (balance aluminum) as the optimum composition for low porosity. The suggested composition corresponds to the composition Ni-25at.%Al. This composition is of little interest since only off-stoichiometric (boron-doped Ni-24at.%Al) alloys are of commercial interest. Their data, however, do suggest that low porosities are also obtainable for nickel-rich Ni_3Al alloys. They also reported an adverse effect of high energy milling which resulted in agglomeration of nickel and aluminum, increasing the apparent particle size and disrupted the aluminum. This observation is surprising since milling is an established method of dispersing constituents; in fact, milling (both wet and dry) was used in the present investigation successfully. Furthermore, German et al.[47] also indicated that fine (3μm) aluminum powder generally resulted in lower densification than coarse aluminum powder and a finer aluminum powder size, by virtue of its high surface area, generally exhibited increased solid state diffusion (for heating rates of the order 50°K/min). Since a porous mass was the goal for this investigation, fine particled aluminum powders (≈1-5μm) and a high heating rate (≈1000-4000°K/min) were utilized in the present investigation. It is worth noting that such fine particles of aluminum and nickel powder, if dispersed properly (we utilized wet milling for that purpose), can result in uniform composition throughout the reacted mass. This is especially important since conventional processing techniques do suffer from the problem of density-assisted segregation of elements in the molten state. German et al.'s [47] observation that increased heating rates improve densification was consistent with the observations of Philpot et al.[46] and Rabin and Wright [45](see later). The most interesting observation, however, was the effect of reaction atmosphere where reactive-sintering (SHS) in an Argon atmosphere resulted in worse densification than in vacuum or Hydrogen. By contrast, since the objective of the present program was to produce porous agglomerates (which could subsequently be de-agglomerated easily), Argon was a logical choice of reaction atmosphere and proved successful. The porosity arises from the dissolution of gases in liquid phases and their rejection during subsequent solidification and cool down. The level of porosity, however, is also likely to be dependent upon the chamber pressure, with lower chamber pressures entailing reduced rejection of dissolved gases, thereby leading to lower porosities. This variable will be investigated in more detail in the Phase II program. Interestingly, despite the high heating rates used in the present investigation, we were able to produce a porous reacted mass, presumably due to the presence of the inert gas Argon in the reaction chamber.

While the above discussion is related to the intermetallic Ni_3Al rather than NiAl (the latter intermetallic being the focus of the present investigation), many of the effects discussed earlier are similar irrespective of the type of intermetallic. Recently, Rabin and Wright [45] have examined the factors affecting the synthesis of iron-aluminides Fe_3Al and FeAl. Note that FeAl, like NiAl, is B2 (ordered b.c.c) structured, while Fe_3Al is DO_3 structured which is based on eight B2 unit cells. Typically, a small exothermic peak was observed prior to the predominant peak that marked a strong reaction, the temperature corresponding to the onset of the first peak (heating rate 10°K/min) was always lower than the lowest eutectic temperature (925°K) and was dependent upon the processing variables like aluminum particle size and heating rates; smaller particle sizes and slower heating rates gave a lower onset temperature. This indicates that the smaller peak is indicative of solid state reactions with a smaller aluminum particle size enhancing the Iron-aluminum particle contacts. Both these observations are consistent with the previous investigations. The maximum reaction temperatures (major peak) for Fe_3Al and FeAl were, respectively, 1253°K and 1493°K. X-ray diffraction of both reaction hot-pressed powder mixtures of compositions Fe-24at.%Al (nominally Fe_3Al) and Fe-50at.%Al (nominally FeAl) exhibited impurity $AlFe_3C_{0.5}$ and B2 FeAl along with desired phase DO_3 Fe_3Al for Fe-24at.%Al and single (only) phase B2 FeAl for Fe-50at.%Al. Like Philpot et al.[46], Rabin and Wright [45] also characterized the reaction path and found that at the leading edges of the reaction front, there was evidence of liquid eutectic within the sites occupied by original aluminum particles. The center of the reaction zone was characterized by large pores at the prior aluminum particle sites surrounded by Al-rich phases (intermetallics) $FeAl_3$ and Fe_2Al_5.

These observations were consistent with those by Philpot et al.[46] who also noted the formation of aluminum-rich intermediate intermetallics before the formation of the final (desired) intermetallic. Homogenization was observed at the trailing edges of the front. Consistent with the observations of Philpot et al.[46] and German et al.[47], faster heating rates resulted in greater densification, presumably due to the larger fraction of available liquid phase. By contrast, the effect of aluminum particle size was in contradiction to that observed by German et al.[47] who reported too fine an aluminum particle size to be detrimental to densities; rather, Rabin and Wright reported that a smaller aluminum particle size resulted in higher sintered densities and found aluminum particles in the 3-10μm range to be optimal. Furthermore, the aluminum particle size was also observed to have a strong effect on the size and distribution of porosity; a 3μm aluminum particle resulted in a more uniform distribution of fine porosity. Thus, since fine aluminum particles are expected to yield compositional homogeneity and a uniform distribution of fine porosity, both of which are critical to producing good quality powder, in contradiction to German et al.'s suggestion, the present investigation utilized both fine particles of aluminum and nickel.

Thus, to summarize, while the above investigations were primarily devoted to generating net shapes by SHS (reaction hot-pressing or liquid phase sintering), in the present program for the production of intermetallic powders, it was necessary to maximize the porosity content while maintaining good compositional (no impurity phases) control. Since the reaction between a liquid phase aluminum and solid nickel powders are likely to result in a shell of intermetallic reaction product which may slow down the kinetics of further reaction, hence, to achieve a complete reaction, it was necessary to use reaction constituents of small particle sizes (aluminum of size 1-5μm and nickel of size 3μm). The use of such small particle sizes were also likely to result in enhanced particle-particle contact, as indicated by Philpot et al.[46], and also generate a more uniform distribution of fine porosity, as has been demonstrated by Rabin and Wright [45]. Although German et al.[47] have indicated that very fine aluminum particles are undesirable, it should be noted that their as-reacted product Ni_3Al was contaminated with the Ni_5Al_3, presumably due to inhomogeneities in dispersion of powder constituents. By contrast, the NiAl powders produced in this investigation were impurity free even in an as-reacted state (no subsequent annealing is necessary to remove any compositional heterogeneity). German et al.[47] have also indicated that the milling of aluminum and nickel particles were unacceptable due to agglomeration problems. However, milling, especially wet milling, is a well established method of dispersing two constituents. A small reactant particle size and good particle dispersion are necessary for obtaining compositional uniformity in the reacted powder.

A new variable which was also observed to influence the purity of the reacted product is the applied pressure for cold pelletization, a higher pressure generally resulted in improved purity. This is probably related to improved inter-particle contact in the cold-pressed pellet. Rabin and Wright [45] have indicated that a higher pelletizing pressure generally resulted in improved sintered densities. However, for the synthesis of powders, excessively high pressures could result in difficulty during the de-agglomeration step.

A major difference between the previously practiced SHS (or liquid phase sintering) processes and the PSHS process developed here is the rate of heating and initiation of reaction. Unlike the previous investigations, where the reaction was initiated in a furnace, the initiation of reaction in this case was achieved by inductive an inductively coupled plasma. As indicated earlier, a higher heating rate is known to initiate the reaction at higher temperatures and only through solid-liquid interactions, which leads to a more uniform network of liquid aluminum interweaved between the nickel particles. While the highest heating rates attainable in conventional heating are of the order of 10-50°K/min, that attainable in a plasma induction system are of the order of 1000-4000°K/min. Hence, the possibilities of any solid state reactions are minimized in our PSHS process which leads to improved purity. Furthermore, with the plasma engulfing the cold-pressed pellet uniformly, a more uniform initiation of reaction is achieved. In the present case, the initiation of the reaction, however, was always at the pellet edges due to the stronger heating effect at the pellet corners; conceivably, a spherical pellet (without any sharp edges) will result in a more uniform and simultaneous initiation of the reaction.

And finally, we believe that the demonstration of the capability of alloying NiAl with ternary alloying elements like iron and titanium using the PSHS process is unique to our laboratories.

In summary, by suitable control of reactant particle sizes, pelletizing pressures, reaction atmosphere, dispersion techniques and rate of heating, we have been able to synthesize porous bodies of NiAl through the PSHS process which are easy to de-agglomerate subsequently to produce fine particles, irregular shaped intermetallic NiAl powders with good compositional control. We are, however, confident that subsequent processing the powder through a laser beam or high frequency induction plasma can spheroidize the irregular shaped powder. Further the economics appear quite promising for producing this powder. As previously stated, an estimate of $10-50/lbs is reasonable based on initial powder cost and the processing required.

Although the investigations into the CAT process were preliminary in nature, the feasibility of producing sub-micron sized powders while preserving the crystal structure and maintaining compositional control was demonstrated in the Phase I program; the Phase II program will concentrate on optimizing the process further.

REFERENCES

1. E.M. Schulson, Res. Mech. Lett., 1, (1981) 111.
2. E.M. Schulson and D.R. Barker, Scripta Met., 17, (1983) 519.
3. A. Ball and R.E. Smallman, Electron Microscopy, 1, (1964) 273.
4. G.W. Groves and A. Kelly, Phil. mag., 8, (1963) 877.
5. R. von Mises, Z. Agnew. Math. Mech., 8, (1928) 161.
6. K.S. Chan, Scripta Met., 24, (1990) 1725.
7. R.D. Noebe, R.R. Bowman, C.L. Cullers and S.V. Raj, HiTemp Review 1990, 20-1.
8. S. Reuss and H. Vehoff, Scripta Met., 24, (1990) 1021.
9. Harmouche and Wolfenden
10. S. Guha, unpublished research.
11. F.R. Stonesifer and R.W. Armstrong, Advances in Research on the Strength and Fracture of Materials, vol. 2A, Physical Metallurgy of Fracture, ed. C.M.R. Taplin, (1977) 1.
12. D.A. Curry and J.F. Knott, Met. Sci. J, 10, (1976) 1.
13. J. Kostrubanic, D.A. Koss, I.E. Locci and M. Nathal, "High Temperature Ordered Intermetallic Alloys", (1991) in press.
14. J.D. Whittenberger, J. mat. Sci., 22, (1987) 394.
15. R.R. Vandervoort, A.K. Mukherjee and J.E. Dorn, Trans. ASM, 59, (1966) 930.
16. W.J. Yang and R.A. Dodd, Met. Sci. J., 7, (1973) 41.
17. J.D. Whittenberger, J. Mat. Sci., 23, (1988) 235.
18. K. Vedula, V. Pathare, I. Aslanidis and R.H. Titran, "High Temperature Ordered Intermetallic Alloys", MRS, (1984) 411.
19. M.F. Singleton, J.L. Murray and P. Nash, in Binary Alloy Phase Diagrams I, eds. T.B. Massalski, (ASM Metals Park, OH, 1986) 142.
20. A.G.Rozner and R.J.Wasilewski, J. Inst. Met., 94 (1966) 169.
21. R.T.Pascoe and C.W.A.Newey, Met. Sci., 5, (1971) 50.
22. K.H.Hahn and K.Vedula, Scripta Met., 23, (1989) 7.

23. E.M.Grala, "Mechanical Properties of Intermetallic Compounds", (1960).

24. A.Ball and R.E.Smallman, Acta Met., 14, (1966) 1349.

25. R.J.Wasilewski, S.R.Butler and J.E.Hanlon, Trans. Met. Soc. AIME, 239 (1967) 1357.

26. C.C.Law and M.J.Blackburn, in Rapidly Solidified Lightweight Disk Material, Interim Report no. FR-18674-4, (1985).

27. S. Guha, P.R. Munroe and I. Baker, Scripta Metall., 23 (1989) 897.

28. Z.A. Munir, Ceramic Bulletin, 67(2), (1988)342.

29. Y.S. Naiborodenko and V.I. Itin, Comn. Explos. Shoch Wave, 11 (1975) 293.

30. J.E. Dualder, J. Phys. D.: Appl. Phys., 10, (1977) 2225.

31. J.E. Dualder, J. Phys. D.: Appl. Phys., 16, (1983) 17.

32. A.M. Dorodnov et al., J. Appl. Mech. Tech. Phys., 22, (1981) 28.

33. I.I. Aksenov et al.. Sev. Tech. Phys. Lett., 7, (1981) 497.

34. W.M. DeCock, J.E. Dualder, VII Int. Symp. on Discharges and Electrical Insulation, (1976) 288.

35. F. Booth, Trans. faraday Soc., 49, (1953) 272.

36. Y.S. Naiborodenko, V.I. Itin and K.V. Savitskii, Sov. Phys. J, 11 (1968) 19.

37. idem, ibid, 11 (1968) 89.

38. Y.S. Naiborodenko, V.I. Itin, A.G. Merzhanov, I.P. Borovinskaya, V.P. Ushakov and V.P. Maslov, ibid, 16, (1973) 872.

39. Y.S. Naiborodenko, V.I. Itin, B.P. Belozerov and V.P. Ushakov, ibid, 16 (1973) 1507.

40. Y.S. Naiborodenko and V.I. Itin, Comb, Explos. Shock Wave, 11 (1975) 293.

41. idem, ibid, 11, (1975) 626.

42. V.M. Maslov, I.P. Borovinskaya and A.G. Morzhanov, ibid, 12, (1976) 631.

43. V.M. Maslov, I.P. Borovinskaya and M.K. Ziatdinov, ibid, 15 (1979) 41.

44. E.A. Nekrasov, Y.M. Maksimov and A.P. Aldushin, ibid, 17, (1981) 140.

45. B.H. Rabin and R.N. Wright, Met. Trans. A, 22, (1991) 277.

46. K.A. Philpot, Z.A. Munir and J.B. Holt, J. Mat. Sci, 22, (1987) 159.

47. R.M. German, A. Bose and D. Sims, U.S. Patent no. 4762558.

APPENDIX I

The results of thermodynamic predictions of the stability of different phases under different pressure and temperature conditions are presented in this section. The following is a description of the format of thermodynamic prediction results only for the case of Ni-to-Al ratio of 1:1; the pressure and temperature range investigated was from 10 atm. to 1×10^{-6} atm. and 2473°K to 773°K respectively. The remaining Sections (different Ni-to-Al ratios) can be interpreted similarly. Under certain conditions, the results are presented over a smaller temperature range since the program did not converge to any specific value (of mole fraction of a certain phase) for some temperatures.

The box #1 specifies the input stoichiometry into the system. For example, in this case, the input to the system included 1 mole each of Ar, Ni and Al and a small value of H_2 (0.005 moles). The partial results of the thermodynamic program are presented in box#2 where the top line specifies the fixed pressure P in atmospheres (note that the notation "1.000 1" implies 1×10^1 atm.). Next, the mole fractions of various phases are presented in a tabular manner where the columns indicate the mole fractions of different phases at a given temperatures T in °K (see line 2) and the rows list the mole fractions of a given phase at increasing temperatures. It should be noted that the sum of mole fractions of different phases at a given temperature add up to unity. Since the input Ar does not enter into the reactions, the correct moles (instead of normalized mole fraction values) of resulting phases are obtained by multiplying the normalized mole fractions of different phases with a multiplier which in turn is obtained by dividing the input Ar moles by the normalized mole fraction of Ar. For example, at 10

1/0.33278) which in turn yields the moles of "Ni" to be ≈1. Note that, all phases, unless otherwise noted are gaseous. Both solid and liquid phases are represented as "(S)" and "(L)" respectively.

The box #3 lists additional possible phases which were considered but were found to be present in very low mole fractions ($< 10^{-8}$) and hence were considered to be practically unstable under these pressure and temperature conditions.

The box #4 represents the stability of different phases under the conditions of 10 atm. and in the temperature range of 1773°K to 1523°K. The box #5 however presents the phase stability results for a reduced pressure i.e. 1 atm; the temperature range varies from 2473°K to 1923°K. This implies that the calculations for specified conditions of 10 atm. pressure and the temperature range of 1473°K to 773°K did not converge to any specific values of mole fractions.

The following sections of the thermodynamic stability results can be interpreted in accordance to the above description for the first 4 boxes.

```
   REACTANTS
   AR  1.0000      0.0000      0.0000      0.0000      0.0000     1.000000  M       0.00        0.000       0.00000
   NI  1.0000      0.0000      0.0000      0.0000      0.0000     1.000000  M       0.00        0.000       0.00000
1  H   2.0000      0.0000      0.0000      0.0000      0.0000     0.005000  M       0.00        0.000       0.00000
   AL  1.0000      0.0000      0.0000      0.0000      0.0000     1.000000  M       0.00        0.000       0.00000

   P, ATM          1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
   T, DEG K            2473      2423      2273      2123      2073      2023      1973      1923

   MOLE FRACTIONS

   AL(L)           3.1751-1 3.2146-1 3.2850-1 3.3206-1 3.3230-1 3.3247-1 3.3258-1 3.3265-1
2  AL              1.5047-2 1.1135-2 4.1875-3 6.8855-4 4.5785-4 2.9820-4 1.8993-4 1.1808-4
   ALH             2.2605-4 1.8257-4 8.9340-5 2.7485-5 2.0150-5 1.4529-5 1.0291-5 7.1511-6
   AR              3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
   H               2.1980-4 1.7686-4 8.5899-5 2.6411-5 1.9396-5 1.4026-5 9.9754 6 6.9700-6
   H2              1.4410-3 1.4842-3 1.5763-3 1.6369-3 1.6441-3 1.6496-3 1.6538-3 1.6568-3
   NI(L)           0.0000 0 0.0000 0 0.0000 0 3.3275-1 3.3276-1 3.3277-1 3.3277-1 3.3278-1
   NI              3.3278-1 3.3278-1 3.3278-1 2.3958-5 1.3996-5 7.9515-6 4.3833-6 2.3387-6
   ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI
3
   AL(S)         NI(S)         NI3AL(S)      NIAL(S)       NI2AL3(S)    NIAL3(S)

   P, ATM          1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
   T, DEG K            1773      1723      1673      1623      1573      1523

   MOLE FRACTIONS

   AL              1.9816-7 8.4581-8 3.4244-8 1.7865-8 6.5677-9 2.2596-9
4  ALH             1.738 -8 8.506 -9 3.982 -9 2.423 -9 1.050 -9 4.300 10
   AR               .9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
   H               3.1594-6 2.0255-6 1.2649-6 7.6772-7 4.5162-7 2.5671-7
   H2              2.4922-3 2.4929-3 2.4932-3 2.4934-3 2.4936-3 2.4937-3
   NI              2.1554-7 9.3020-8 3.8167-8 1.0856-8 3.8724-9 1.2886-9
   NIAL(S)         4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1

5  AL(S)         AL(L)         NI(S)         NI(L)         NI3AL(S)     NI2AL3(S)     NIAL3(S)

   P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
   T, DEG K            2473      2423      2273      2123      2073      2023      1973      1923

   AL(L)           2.3553-1 2.6576-1 3.1025-1 3.2567-1 3 2808-1 3.2973-1 3.3084-1 3.3157-1
   AL              9.6740-2 6.6610-2 2.2329-2 7.0214-3 4.6379-3 3.0071-3 1.9094-3 1.1847-3
   ALH             5.1365-4 4.1128-4 1.9913-4 8.6211-5 6.3301-5 4.5706-5 3.2414-5 2.2547-5
6  AR              3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278 1 3.3278-1
   H               4.9947-4 3.9843-4 1.9146-4 8.2843-5 6.0934-5 4.4123-5 3.1420-5 2.1976-5
   H2              1.1573-3 1.2591-3 1.4686-3 1.5794-3 1.6018-3 1.6190-3 1.6320-3 1.6416-3
   NI(L)           3.2569-1 3.2833-1 3.3168-1 3.3253-1 3.3264-1 3.3270-1 3.3273-1 3.3276-1
   NI              7.0863-3 4.4519-3 1.1030-3 2.4430-4 1.4178-4 8.0183-5 4.4066-5 2.3464-5
   ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

   AL(S)         NI(S)         NI3AL(S)      NIAL(S)       NI2AL3(S)    NIAL3(S)

   P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
```

```
 T, DEG K           1773     1723      1673      1623      1573      1523      1473      1423      1373      1323

 AL            2.039 -6 8.732 -7 3.551 -7 1.786 -7 6.568 -8 2.260 -8 7.226 -9 4.192 -9 1.410 -9 4.777-10
 ALH           5.649 -8 2.776 -8 1.305 -8 7.662 -9 3.319 -9 1.360 -9 5.240-10 3.710-10 1.546-10 6.592-11
 AR            4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H             9.9841-6 6.4022-6 3.9989-6 2.4273-6 1.4280-6 8.1175-7 4.4434-7 2.3330-7 1.1696-7 5.5[illegible]8-8
 H2            2.4887-3 2.4905-3 2.4918-3 2.4925-3 2.4932-3 2.4934-3 2.4935-3 2.4936-3 2.4937-3 2.4938-3
 NI            2.095 -6 9.010 -7 3.681 -7 1.086 -7 3.872 -8 1.289 -8 3.972 -9 5.723-10 1.184-10 1.981-11
 NI3AL(S)      0.000  0 0.000  0 0.000  0 3.840 -8 2.242 -9 4.792 -9 4.213-16 0.000  0 0.000  0 0.000  0
 NIAL(S)       4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          AL(L)          NI(S)          NI(L)          NI2AL3(S)    NIAL3(S)

 P, ATM        1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)         0.0000 0 0.0000 0 0.0000 0 2.4517-1 2.7933-1 2.9983-1 3.1252-1 3.2046-1
 AL            3.3225-1 3.3226-1 3.3219-1 8.7324-2 5.3246-2 3.2805-2 2.0158-2 1.2247-2
 ALH           2.7464-4 3.1772-4 5.6567-4 2.8469-4 2.0496-4 1.4628-4 1.0305-4 7.1419-5
 AR            3.3253-1 3.3258-1 3.3276-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             1.7721-3 1.5201-3 7.0291-4 2.7356-4 1.9730-4 1.4122-4 9.9889-5 6.9610-5
 H2            6.3927-4 7.4396-4 1.0295-3 1.3848-3 1.4628-3 1.5201-3 1.5624-3 1.5934-3
 NI(L)         0.0000 0 0.0000 0 3.1155-1 3.2974-1 3.3115-1 3.3190-1 3.3231-1 3.3254-1
 NI            3.3253-1 3.3258-1 2.1208-2 3.0384-3 1.6277-3 8.7473-4 4.6521-4 2.4256-4
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)          NI(S)          NI3AL(S)      NIAL(S)        NI2AL3(S)    NIAL3(S)

 P, ATM        1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K          1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL            2.0579-5 8.8261-6 3.5945-6 1.7065-6 6.5677-7 2.2596-7 7.2262-8 2.1317-8 5.7495-9 3.8686-9
 ALH           1.799 -7 8.860 -8 4.175 -8 2.422 -8 1.049 -8 4.299 -9 1.657 -9 5.967-10 1.993-10 1.688-10
 AR            4.9873-1 4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H             3.1304-5 2.0217-5 1.2635-5 7.6719-6 4.5143-6 2.5665-6 1.4050-6 7.3771-7 3.6984-7 1.7613-7
 H2            2.4778-3 2.4836-3 2.4874-3 2.4899-3 2.4915-3 2.4925-3 2.4931-3 2.4934-3 2.4936-3 2.4937-3
 NI            2.076 -5 8.915 -6 3.636 -6 1.086 -6 3.872 -7 1.289 -7 3.972 -8 1.125 -8 2.902 -9 2.447-10
 NI3AL(S)      0.000  0 0.000  0 0.000  0 3.586 -7 1.400 -7 4.855 -8 1.603 -8 4.948 -9 2.538-15 0.000  0
 NIAL(S)       4.9871-1 4.9873-1 4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          AL(L)          NI(S)          NI(L)          NI2AL3(S)    NIAL3(S)

 P, ATM        5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)         5.1400-2 1.6297-1 2.8446-1 3.1830-1 3.2328-1 3.2664-1 3.2809-1 3.3037-1
 AL            2.8061-1 1.6920-1 4.8033-2 1.4356-2 9.4110-3 6.0705-3 3.8414-3 2.3780-3
 ALH           7.7237-4 6.0408-4 2.8370-4 1.2190-4 8.9446-5 6.4568-5 4.5789-5 3.1855-5
 AR            3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             7.5106-4 5.8520-4 2.7277-4 1.1714-4 8.6101-5 6.2331-5 4.4385-5 3.1048-5
 H2            9.0219-4 1.0693-3 1.3857-3 1.5444-3 1.5761-3 1.6004-3 1.6188-3 1.6324-3
 NI(L)         3.1227-1 3.2147-1 3.3041-1 3.3228-1 3.3249-1 3.3262-1 3.3269-1 3.3273-1
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NI              2.0555-2 1.1309-2 2.3728-3 4.9951-4 2.8769-4 1.6187-4 8.8654-5 4.7100-5
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)        NI(S)         NI3AL(S)     NIAL(S)       NI2AL3(S)    NIAL3(S)

 P, ATM          5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K            1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL              4.094 -6 1.754 -6 7.138 -7 3.573 -7 1.314 -7 4.519 -8 1.445 -8 7.464 -9 2.476 -9 8.283-10
 ALH             8.018 -8 3.942 -8 1.855 -8 1.084 -8 4.693 -9 1.923 -9 7.410-10 4.672-10 1.919-10 8.083-11
 AR              4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H               1.4114-5 9.0517-6 5.6544-6 3.4324-6 2.0195-6 1.1480-6 6.2838-7 3.2993-7 1.6540-7 7.8768-8
 H2              2.4866-3 2.4892-3 2.4909-3 2.4920-3 2.4930-3 2.4932-3 2.4935-3 2.4936-3 2.4937-3 2.4937-3
 NI              4.174 -6 1.794 -6 7.324 -7 2.171 -7 7.745 -8 2.577 -8 7.945 -9 1.285 -9 2.696-10 4.571-11
 NI3AL(S)        0.0000 0 0.0000 0 0.0000 0 7.4632-8 4.1172-9 9.5832-9 3.2058-9 0.0000 0 0.0000 0 0.0000 0
 NIAL(S)         4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         NI(S)        NI(L)         NI2AL3(S)    NIAL3(S)

 P, ATM          1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K            2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL              3.3223-1 3.3223-1 3.3226-1 3.3235-1 3.3240-1 3.3245-1 3.3250-1 3.3254-1 1.0063-2 4.6557-3
 ALH             5.0731-6 6.7874-6 1.6850-5 4.0191-5 5.1699-5 6.4889-5 9.3498-5 1.1584-4 6.2443-6 3.3840-6
 AR              3.3223-1 3.3224-1 3.3228-1 3.3239-1 3.3245-1 3.3251-1 3.3260-1 3.3265-1 4.9356-1 4.9632-1
 H               3.2736-3 3.2477-3 3.0407-3 2.3872-3 2.0466-3 1.6785-3 1.1881-3 8.5974-4 6.7247-4 4.6040-4
 H2              2.1815-5 3.3957-5 1.3263-4 4.4825-4 6.1308-4 7.9087-4 1.0222-3 1.1755-3 2.1285-3 2.2497-3
 NI(L)           0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.3200-1 2.8250-1 0.0000 0 0.0000 0
 NI              3.3223-1 3.3224-1 3.3228-1 3.3239-1 3.3245-1 3.3251-1 1.0059-1 5.0155-2 1.0069-2 4.6590-3
 NIAL(S)         0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.8350-1 4.9166-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         NI(S)         NI3AL(S)     NI2AL3(S)    NIAL3(S)

 P, ATM          1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K            1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL              2.0790-3 8.8901-4 3.6173-4 1.7874-4 6.5690-5 2.2597-5 7.2264-6 2.1317-6 5.7495-7 1.4036-7
 ALH             1.759 -6 8.745 -7 4.150 -7 2.405 -7 1.045 -7 4.289 -8 1.655 -8 5.963 -9 1.993 -9 6.124-10
 AR              4.9764-1 4.9826-1 4.9854-1 4.9868-1 4.9872-1 4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H               3.0672-4 1.9866-4 1.2495-4 7.6201-5 4.4962-5 2.5606-5 1.4032-5 7.3722-6 3.6972-6 1.7610-6
 H2              2.3340-3 2.3915-3 2.4300-3 2.4552-3 2.4711-3 2.4809-3 2.4867-3 2.4901-3 2.4919-3 2.4929-3
 NI              2.0807-3 8.8989-4 3.6214-4 1.0862-4 3.8732-5 1.2807-5 3.9726-6 1.1253-6 2.9023-7 6.7435-8
 NI3AL(S)        0.0000 0 0.0000 0 0.0000 0 3.5180-5 1.3531-5 4.8765-6 1.6352-6 5.0617-7 1.4236-7 3.6460-8
 NIAL(S)         4.9556-1 4.9737-1 4.9818-1 4.9847-1 4.9856-1 4.9871-1 4.9874-1 4.9875-1 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         NI(S)        NI(L)         NI2AL3(S)    NIAL3(S)

 P, ATM          1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K            1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AL              2.104 -6 2.137 -7 7.841 -8 8.638 -9 3.162 -9 5.021-10 5.438-11 4.616-12 2.946-13 1.342-14 4.084-16
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 ALH            1.177 -8 1.563 -9 7.674-10 1.161-10 6.007-11 1.394-11 2.295-12 3.099-13 3.314-14 2.691-15 1.573-16
 AR             4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H              7.919 -7 3.339 -7 1.309 -7 4.722 -8 1.556 -8 4.597 -9 1.201 -9 2.[illegible]16-10 5.194-11 8.144-12 1.008-12
 H2             2.4934-3 2.4936-3 2.4938-3 2.4937-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3
 NIAL(S)        4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)          AL(L)          NI(S)          NI(L)          NI             NI3AL(S)       NI2AL3(S)      NIAL3(S)

 P, ATM         1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL             3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3224-1
 ALH            5.1483-9 6.9429-9 1.8407-8 5.5083-8 8.3797-8 1.2811-7 1.9988-7 3.1845-7 5.1775-7 8.5601-7
 AR             3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3224-1
 H              3.3222-3 3.3222-3 3.3221-3 3.3205-3 3.3190-3 3.3160-3 3.3099-3 3.2972-3 3.2698-3 3.2104-3
 H2             2.2467-8 3.5532-8 1.5831-7 8.6724-7 1.6123-6 3.0867-6 6.0930-6 1.2405-5 2.5993-5 5.5605-5
 NI             3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3223-1 3.3224-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)          AL(L)          NI(S)          NI(L)          NI3AL(S)       NIAL(S)        NI2AL3(S)      NIAL3(S)

 P, ATM         1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL             3.3226-1 3.3231-1 3.3237-1 3.3232-1 7.9139-2 2.3994-2 7.3630-3 2.1434-3 5.7581-4 1.4041-4
 ALH            1.4252-6 2.3423-6 3.6935-6 6.4620-6 3.0284-6 1.2786-6 5.0452-7 1.8471-7 6.2338-8 1.9265-8
 AR             3.3227-1 3.3231-1 3.3238-1 3.9712-1 4.7516-1 4.9174-1 4.9663-1 4.9813-1 4.9858-1 4.9871-1
 H              3.0833-3 2.8321-3 2.4116-3 2.0531-3 1.3030-3 7.6334-4 4.2785-4 2.2837-4 1.1566-4 5.5395-5
 H2             1.1897-4 2.4430-4 4.5424-4 9.5579-4 1.7227-3 2.0764-3 2.2690-3 2.3764-3 2.4350-3 2.4658-3
 NI             3.3227-1 3.3231-1 3.3238-1 2.0275-1 4.6662-2 1.3684-2 4.0476-3 1.1315-3 2.9067-4 6.7460-5
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 6.4788-2 1.6240-2 5.1557-3 1.6579-3 5.0605-4 1.4260-4 3.6484-5
 NIAL(S)        0.0000 0 0.0000 0 0.0000 0 0.0000 0 3.7977-1 4.6259-1 4.8761-1 4.9548-1 4.9786-1 4.9853-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          AL(L)          NI(S)          NI(L)          NI2AL3(S)      NIAL3(S)

 P, ATM         1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AL             3.065 -5 5.906 -6 9.804 -7 1.410 -7 1.675 -8 1.344 -8 4.872 -9 1.790 -9 2.946-10 1.342-11 4.084-13
 AR             4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H              2.498 -5 1.055 -5 4.139 -6 1.495 -6 4.919 -7 1.454 -7 3.797 -8 8.509 -9 1.643 -9 2.575-10 3.187-11
 H2             2.4812-3 2.4885-3 2.4917-3 2.4930-3 2.4935-3 2.4937-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3
 NI             1.394 -5 2.529 -6 3.957 -7 5.237 -8 5.728 -9 6.049-11 8.635-13 6.852-15 6.197-17 9.149-19 7.826-21
 NI3AL(S)       6.3571-6 1.6887-6 2.9633-7 4.4292-8 5.5131-9 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NIAL(S)        4.9870-1 4.9874-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          AL(L)          ALH            NI(S)          NI(L)          NI2AL3(S)      NIAL3(S)
NI1AL1   OUT     15113   1-01-80   5:35a
NI1AL2   OUT     11730   1-01-80   5:43a
NI2AL3   OUT     18864   1-01-80   5:53a
NI2AL5   OUT      5279   1-01-80   5:56a
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REACTANTS
AR  1.0000   0.0000    0.0000    0.0000    0.0000   1.000000  M    0.00     0.000    0.00000
NI  1.0000   0.0000    0.0000    0.0000    0.0000   2.000000  M    0.00     0.000    0.00000
H   2.0000   0.0000    0.0000    0.0000    0.0000   0.005000  M    0.00     0.000    0.00000
AL  1.0000   0.0000    0.0000    0.0000    0.0000   3.000000  M    0.00     0.000    0.00000

P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

AL(L)          4.8016-1 4.9112-1 4.9639-1 4.9923-1 4.9934-1 4.9943-1 4.9948-1 4.9952-1
AL             1.1285-2 8.3506-3 3.1405-3 3.4456-4 2.2911-4 1.4923-4 9.5044-5 5.9088-5
ALH            1.3627-4 1.1042-4 5.4401-5 1.3754-5 1.0083-5 7.2705-6 5.1498-6 3.5785-6
AR             1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
H              1.3250-4 1.0697-4 5.2306-5 1.3217-5 9.7062-6 7.0186-6 4.9918-6 3.4879-6
H2             6.9826-4 7.2394-4 7.7929-4 8.1915-4 8.2274-4 8.2550-4 8.2757-4 8.2911-4
NI(L)          0.0000 0 0.0000 0 0.0000 0 3.3304-1 3.3305-1 3.3305-1 3.3305-1 3.3305-1
NI             3.3306-1 3.3306-1 3.3306-1 1.1989-5 7.0038-6 3.9790-6 2.1935-6 1.1703-6
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

AL(L)          2.4967-1 2.4968-1 2.4968-1 2.4968-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 0.0000 0 1.0437-8
AL             1.8027-5 9.9490-6 5.2932-6 2.7056-6 1.3234-6 6.1683-7 2.7257-7 1.1355-7 5.1803-8 3.2105-8
ALH            1.5802-6 1.0003-6 6.1544-7 3.6700-7 2.1149-7 1.1738-7 6.2501-8 3.1786-8 1.7961-8 1.4011-8
AR             2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 4.9875-1 4.9875-1
H              1.5812-6 1.0138-6 6.3318-7 3.8431-7 2.2608-7 1.2852-7 7.0346-8 3.6934-8 3.6986-8 1.7613-8
H2             1.2469-3 1.2474-3 1.2478-3 1.2481-3 1.2482-3 1.2483-3 1.2484-3 1.2484-3 2.4937-3 2.4937-3
NIAL(S)        4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 0.0000 0 0.0000 0
NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

AL(S)        NI(S)        NI(L)        NI           NI3AL(S)     NIAL3(S)

P, ATM         1.0000 1 1.0000 1 1.0000 1
T, DEG K           1273     1223     1173

AL(L)          7.3922-8 5.6875-8 5.6302-8
AL             1.073 -8 3.2742-9 9.004-10
AR             4.9875-1 4.9875-1 4.9875-1
H2             2.4938-3 2.4938-3 2.4938-3
NI2AL3(S)      4.9875-1 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

AL(S)        ALH          H            NI(S)        NI(L)        NI           NI3AL(S)     NIAL(S)      NIAL3(S)

P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

AL(L)          4.5092-1 4.6605-1 4.8831 1 4.9603-1 4.9723-1 4.9806-1 4.9861-1 4.9898-1
AL             4.8410-2 3.3332-2 1.1174-2 3.5136-3 2.3209-3 1.5048-3 9.5550-4 5.9283-4
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 ALH            2.5704-4 2.0581-4 9.9650-5 4.3141-5 3.1677-5 2.2072-5 1.6220-5 1.1283-5
 AR             1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H              2.4994-4 1.9938-4 9.5812-5 4.1456-5 3.0492-5 2.2080-5 1.5723-5 1.0997-5
 H2             5.7915-4 6.3005-4 7.3491-4 7.9034-4 8.0156-4 8.1016-4 8.1667-4 8.2150-4
 NI(L)          3.2951-1 3.3083-1 3.3250-1 3.3293-1 3.3299-1 3.3302-1 3.3303-1 3.3304-1
 NI             3.5461-3 2.2278-3 5.5198-4 1.2225-4 7.0947-5 4.0125-5 2.2052-5 1.1742-5
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)          NI(S)          NI3AL(S)       NIAL(S)        NI2AL3(S)      NIAL3(S)

 P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL(L)          2.4950-1 2.4959-1 2.4963-1 2.4966-1 2.4967-1 2.4968-1 2.4968-1 2.4969-1 0.0000 0 0.0000 0
 AL             1.8039-4 9.9526-5 5.2943-5 2.7058-5 1.3235-5 6.1685-6 2.7258-6 1.1355-6 3.4447-7 1.4318-7
 ALH            4.9917-6 3.1612-6 1.9453-6 1.1602-6 6.6869-7 3.7116-7 1.9763-7 1.0051-7 3.7768-8 1.9760-8
 AR             2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 4.9875-1 4.9875-1
 H              4.9951-6 3.2037-6 2.0014-6 1.2150-6 7.1482-7 4.0636-7 2.2244-7 1.1679-7 1.1696-7 5.5698-8
 H2             1.2434-3 1.2453-3 1.2465-3 1.2473-3 1.2477-3 1.2481-3 1.2482-3 1.2483-3 2.4937-3 2.4937-3
 NIAL(S)        4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 0.0000 0 0.0000 0
 NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          NI(S)          NI(L)          NI             NI3AL(S)       NIAL3(S)

 P, ATM         1.0000 0 1.0000 0 1.0000 0
 T, DEG K           1273     1223     1173

 AL(L)          0.0000 0 1.7635-8 6.4872-8
 AL             4.7032-8 3.2739-8 9.0041-9
 AR             4.9875-1 4.9875-1 4.9875-1
 H              2.5045-8 1.0559-8 4.1406-9
 H2             2.4937-3 2.4938-3 2.4938-3
 NI2AL3(S)      4.9875-1 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          ALH            NI(S)          NI(L)          NI             NI3AL(S)       NIAL(S)        NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL(L)          0.0000 0 0.0000 0 0.0000 0 3.6992-1 4.2015-1 4.5051-1 4.6938-1 4.8121-1 2.4417-1 2.4647-1
 AL             4.9915-1 4.9915-1 4.9914-1 1.2944-1 7.9263-2 4.8948-2 3.0115-2 1.8309-2 5.4822-3 3.1985-3
 ALH            2.3563-4 2.7757-4 4.2185-4 2.2958-4 1.6886-4 1.2233-4 8.7086-5 6.0808-5 3.6435-5 2.4255-5
 AR             1.6646-1 1.6648-1 1.6652-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 2.4969-1 2.4969-1
 H              1.0120-3 8.8402-4 5.0673-4 2.2061-4 1.6254-4 1.1809-4 8.4415-5 5.9268-5 3.5762-5 2.4016-5
 H2             2.0849-4 2.5159-4 3.6835-4 6.0755-4 6.6694-4 7.1243-4 7.4689-4 7.7260-4 1.2123-3 1.2243-3
 NI             3.3293-1 3.3295-1 3.3304-1 3.3306-1 3.3306-1 3.3306-1 3.3306-1 3.3306-1 4.5567-7 1.6952-7
 NIAL(S)        0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9938-1 4.9938-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)          NI(S)          NI(L)          NI3AL(S)       NI2AL3(S)      NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
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 T, DEG K            1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL(L)            2.4786-1 2.4868-1 2.4915-1 2.49[illegible]-1 2.4955-1 2.4963-1 2.4966-1 2.4968-1 0.0000 0 0.0000 0
 AL               1.8157-3 9.9885-4 5.3044-4 2.7035-4 1.3241-4 6.1698-5 2.7260-5 1.1356-5 1.2249-6 4.6711-7
 ALH              1.5768-5 9.9868-6 6.1470-6 3.6670-6 2.1138-6 1.1734-6 6.2489-7 3.1783-7 4.2468-8 2.0386-8
 AR               2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 4.9875-1 4.9875-1
 H                1.5779-5 1.0121-5 6.3242-6 3.8400-6 2.2596-6 1.2847-6 7.0333-7 3.6930-7 3.6984-7 1.7613-7
 H2               1.2327-3 1.2384-3 1.2422-3 1.2447-3 1.2463-3 1.2472-3 1.2478-3 1.2481-3 2.4936-3 2.4937-3
 NI               5.982 -8 1.990 -8 6.202 -9 1.799 -9 4.819-10 1.183-10 2.640-11 5.295-12 6.671-12 8.787-13
 NIAL(S)          4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 0.0000 0 0.0000 0
 NI2AL3(S)        0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9875-1 4.9875-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)        NI(S)        NI(L)        NI3AL(S)     NIAL3(S)

 P, ATM           1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K            1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AL               5.548 -8 5.176 -8 5.056 -8 1.446 -8 2.841 -9 4.743-10 6.563-11 7.302-12 6.292-13 4.007-14 1.779-15
 AR               4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H                7.920 -8 3.339 -8 1.309 -8 4.729 -9 1.556 -9 4.597-10 1.201-10 2.716-11 5.194-12 8.144-13 1.008-13
 H2               2.4937-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3
 NI2AL3(S)        4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 NIAL3(S)         0.0000 0 0.0000 0 0.0000 0 4.5073-8 4.3315-8 3.8544-8 3.7259-8 3.6966-8 3.6910-8 3.6902-8 3.6900-8
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)        ALH          NI(S)        NI(L)        NI           NI3AL(S)     NIAL(S)

 P, ATM           5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K            2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)            1.0393-1 2.5446-1 4.7541-1 4.9234-1 4.9483-1 4.9651-1 4.9764-1 4.9838-1
 AL               3.9512-1 2.4468-1 2.4037-2 7.1840-3 4.7094-3 3.0378-3 1.9223-3 1.1900-3
 ALH              5.3389-4 4.4261-4 1.4197-4 6.1000-5 4.4760-5 3.2311-5 2.2914-5 1.5941-5
 AR               1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H                5.1915-4 4.2878-4 1.3650-4 5.8617-5 4.3086-5 3.1192-5 2.2211-5 1.5537-5
 H2               3.0613-4 3.9695-4 6.9341-4 7.7283-4 7.8872-4 8.0089-4 8.1008-4 8.1690-4
 NI(L)            0.0000 0 0.0000 0 3.3187-1 3.3281-1 3.3291-1 3.3297-1 3.3301-1 3.3303-1
 NI               3.3306-1 3.3306-1 1.1874-3 2.4996-4 1.4396-4 8.1002-5 4.4364-5 2.3570-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

 P, ATM           5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K            1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL(L)            2.4932-1 2.4948-1 2.4958-1 2.4963-1 2.4966-1 2.4968-1 2.4968-1 2.4969-1 0.0000 0 0.0000 0
 AL               3.6104-4 1.9913-4 1.0591-4 5.4122-5 2.6472-5 1.2337-5 5.4516-6 2.2711-6 6.7036-7 2.6188-7
 ALH              7.0561-6 4.4691-6 2.7505-6 1.6406-6 9.4559-7 5.2487-7 2.7949-7 1.4215-7 5.1971-8 2.5556-8
 AR               2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 4.9875-1 4.9875-1
 H                7.0609-6 4.5293-6 2.8298-6 1.7180-6 1.0108-6 5.7465-7 3.1457-7 1.6517-7 1.6540-7 7.8768-8
 H2               1.2414-3 1.2439-3 1.2456-3 1.2468-3 1.2475-3 1.2479-3 1.2481-3 1.2483-3 2.4937-3 2.4937-3
 NI               1.189 -8 3.967 -9 1.238 -9 3.594-10 9.634-11 2.366-11 5.279-12 1.059-12 2.948-13 3.745-14
 NIAL(S)          4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 0.0000 0 0.0000 0
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 P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K          1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL            3.3900-4 1.3522-4 5.3553 5 1.1926-4 4.3830-5 1.5078-5 4.8216-6 1.4223-6 3.8362-7 9.3649-8
 ALH           2.865 -7 1.329 -7 6.143  8 1.605 -7 6.972 -8 2.862 -8 1.104 -8 3.978 -9 1.330 -9 4.086-10
 AR            1.6646-1 1.6650-1 1.6652-1 3.3275-1 3.3277-1 3.3277-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             1.0272-4 6.6427-5 4.1746-5 5.0845-5 3.0000-5 1.7085-5 9.3627-6 4.9189-6 2.4669-6 1.1750-6
 H2            7.8081-4 7.9922-4 8.1167-4 1.6382-3 1.6488-3 1.6553-3 1.6592-3 1.6614-3 1.6627-3 1.6633-3
 NI(S)         0.0000 0 4.9898-1 4.9933-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)         4.9829-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI            1.4343-3 6.5482-4 2.7317-4 7.2475-5 2.5843-5 8.5988-6 2.6506-6 7.5082-7 1.9365-7 4.4994-8
 NI3AL(S)      0.0000 0 0.0000 0 0.0000 0 4.9914-1 4.9916-1 4.9916-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)       3.3259-1 3.3286-1 3.3298-1 1.6623-1 1.6633-1 1.6637-1 1.6638-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)        AL(L)         NI2AL3(S)    NIAL3(S)

 P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K          1273     1223     1173     1123    .1073     1023      973      923      873      823      773

 AL            2.045 -8 3.941 -9 6.595-10 9.405-11 1.118-11 1.078-12 8.171-14 4.679-15 1.930-16 5.398-18 9.501-20
 AR            3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             5.284 -7 2.228 -7 8.736 -8 3.156 -8 1.038 -8 3.067 -9 8.011-10 1.812-10 3.466-11 5.434-12 6.723-13
 H2            1.6636-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)      4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)       1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)        AL(L)         ALH            NI(S)          NI(L)          NI             NI2AL3(S)    NIAL3(S)

 P, ATM        1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL            2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1
 ALH           1.4540-9 1.9609-9 5.1988-9 1.5788-8 2.3682-8 3.6227-8 5.6580-8 9.0357-8 1.4766-7 2.4684-7
 AR            1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1 1.2484-1
 H             1.2484-3 1.2484-3 1.2484-3 1.2482-3 1.2480-3 1.2477-3 1.2467-3 1.2448-3 1.2408-3 1.2318-3
 H2            3.1727-9 5.0177-9 2.2357-8 1.2254-7 2.2798-7 4.3699-7 8.6436-7 1.7681-6 3.7429-6 8.1867-6
 NI            6.2422-1 6.2422-1 6.2422-1 6.2422-1 6.2422-1 6.2422-1 6.2422-1 6.24 2-1 6.2422-1 6.2422-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)        AL(L)         NI(S)          NI(L)          NI3AL(S)       NIAL(S)        NI2AL3(S)    NIAL3(S)



 AL            2.4969-1 2.4970-1 2.4971-1 1.4174-1 5.3648-2 1.6084-2 4.9197-3 1.4307-3 3.8423-4 9.3687-5
 ALH           4.2077-7 7.2404-7 1.2299-6 3.0880-6 2.0530-6 8.5714-7 3.3741-7 1.2329-7 4.1598-8 1.2855-8
 AR            1.2485-1 1.2485-1 1.2486-1 2.8632-1 3.2211-1 3.2964-1 3.3183-1 3.3250-1 3.3270-1 3.3276-1
 H             1.2113-3 1.1651-3 1.0689-3 1.3999-3 8.8333-4 5.1171-4 2.8588-4 1.5244-4 7.7180-5 3.6962-5
 H2            1.8363-5 4.1343-5 8.9230-5 7.3015-4 1.1678-3 1.3919-3 1.5160-3 1.5862-3 1.6249-3 1.6453-3
 NI            6.2423-1 6.2425-1 6.2428-1 1.3090-1 3.1632-2 9.1730-3 2.7045-3 7.5527-4 1.9396-4 4.5012-5
 NI3AL(S)      0.0000 0 0.0000 0 0.0000 0 4.3091-1 4.9417-1 4.9792-1 4.9885-1 4.9909-1 4.9915-1 4.9916-1
 NIAL(S)       0.0000 0 0.0000 0 0.0000 0 0.0000 0 9.6394-2 1.4528-1 1.5989-1 1.6448-1 1.6587-1 1.6626-1
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ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          AL(L)          NI(S)          NI(L)          NI2AL3(S)     NIAL3(S)


 P, ATM             1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K               1273     1223     1173     1123     1073     1023      973      923      873      823      773


 AL                 2.045 -5 3.941 -6 6.595 -7 9.405 -8 1.118 -8 1.078 -9 8.171-11 4.679-12 1.930-13 5.398-15 9.501-17
 AR                 3.3277-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H                  1.667 -5 7.038 -6 2.762 -6 9.977 -7 3.282 -7 9.700 -8 2.533 -8 5.731 -9 1.096 -9 1.718-10 2.126-11
 H2                 1.6555-3 1.6604-3 1.6625-3 1.6634-3 1.6637-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI                 9.304 -6 1.687 -6 2.640 -7 3.494 -8 3.822 -9 3.358-10 2.292-11 1.167-12 4.212-14 1.012-15 1.498-17
 NI3AL(S)           4.9916-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)            1.6636-1 1.6638-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          AL(L)          ALH            NI(S)          NI(L)          NI2AL3(S)     NIAL3(S)
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 AL(S)        AL(L)          ALH           NI(S)          NI(L)          NI2AL3(S)     NIAL3(S)
 REACTANTS
 AR  1.0000     0.0000       0.0000        0.0000         0.0000        3.000000  M      0.00          0.000          0.00000
 NI  1.0000     0.0000       0.0000        0.0000         0.0000        4.000000  M      0.00          0.000          0.00000
 H   2.0000     0.0000       0.0000        0.0000         0.0000        0.005000  M      0.00          0.000          0.00000
 AL  1.0000     0.0000       0.0000        0.0000         0.0000        8.000000  M      0.00          0.000          0.00000

 P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
 T, DEG K           2473      2423      2273      2123      2073      2023      1973      1923

 AL(L)          5.2255-1 5.2530-1 5.3019-1 5.3273-1 5.3287-1 5.3297-1 5.3304-1 5.3308-1
 AL             1.0527-2 7.7898-3 2.9297-3 4.1230-4 2.7415-4 1.7856-4 1.1373-4 7.0705-5
 ALH            7.9505-5 6.5036-5 3.2665-5 9.4613-6 6.9474-6 5.0155-6 3.5550-6 2.4726-6
 AR             1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1
 H              7.7309-5 6.3003-5 3.1407-5 9.0917-6 6.6876-6 4.8417-6 3.4467-6 2.4099-6
 H2             2.5482-4 2.6920-4 3.0119-4 3.2395-4 3.2640-4 3.2829-4 3.2972-4 3.3078-4
 NI(L)          0.0000 0 0.0000 0 0.0000 0 2.6656-1 2.6657-1 2.6657-1 2.6658-1 2.6658-1
 NI             2.6658-1 2.6658-1 2.6658-1 1.4346-5 8.3806-6 4.7613-6 2.6247-6 1.4004-6
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
 T, DEG K           1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

 AL(L)          3.6345-1 3.6346-1 3.6346-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 2.8551-1 2.8551-1
 AL             1.9616-5 1.0826-5 5.7599-6 2.9441-6 1.4401-6 6.7121-7 2.9660-7 1.2356-7 7.5744-8 2.7476-8
 ALH            9.9393-7 6.2932-7 3.8722-7 2.3093-7 1.3308-7 7.3866-8 3.9331-8 2.0003-8 1.5187-8 6.9346-9
 AR             2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 4.2827-1 4.2827-1
 H              9.9460-7 6.3779-7 3.9838-7 2.4182-7 1.4226-7 8.0871-8 4.4268-8 2.3242-8 1.8305-8 8.7173-9
 H2             4.5334-4 4.5371-4 4.5395-4 4.5410-4 4.5420-4 4.5428-4 4.5431-4 4.5432-4 7.1376-4 7.1377-4
 NIAL(S)        3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 0.0000 0 0.0000 0
 NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.8551-1 2.8551-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)        NI(S)        NI(L)        NI           NI3AL(S)     NIAL3(S)

 P, ATM         1.0000 1 1.0000 1 1.0000 1
 T, DEG K           1273      1223      1173

 AL(L)          2.8551-1 2.8551-1 2.8551-1
 AR             4.2827-1 4.2827-1 4.2827-1
 H2             7.1378-4 7.1378-4 7.1378-4
 NI2AL3(S)      2.8551-1 2.8551-1 2.8551-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)        AL           ALH          H            NI(S)        NI(L)        NI           NI3AL(S)     NIAL(S)      NI

 P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K           2473      2423      2273      2123      2073      2023      1973      1923

 AL(L)          4.7512-1 4.9316-1 5.1972-1 5.2892-1 5.3036-1 5.3134-1 5.3200-1 5.3244-1
 AL             5.7885-2 3.9863-2 1.3367-2 4.2040-3 2.7770-3 1.8006-3 1.1433-3 7.0937-4
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ALH           1.5630-4 1.2883-4 6.5892-5 2.9291-5 2.1618-5 1.5670-5 1.1146-5 7.7695-6
AR            1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1
H             1.5198-4 1.2480-4 6.3354-5 2.8147-5 2.0810-5 1.5128-5 1.0804-5 7.5727-6
H2            1.7908-4 2.0641-4 2.6860-4 3.0450-4 3.1201-4 3.1782-4 3.2225-4 3.2555-4
NI(L)         2.6234-1 2.6391-1 2.6592-1 2.6643-1 2.6649-1 2.6653-1 2.6655-1 2.6656-1
NI            4.2402-3 2.6643-3 6.6034-4 1.4628-4 8.4890-5 4.8011-5 2.6386-5 1.4050-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

P, ATM        1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
T, DEG K          1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

AL(L)         3.6327-1 3.6336-1 3.6341-1 3.6344-1 3.6346-1 3.6346-1 3.6347-1 3.6347-1 2.8551-1 2.8551-1
AL            1.9629-4 1.0830-4 5.7610-5 2.9444-5 1.4402-5 6.7122-6 2.9661-6 1.2356-6 7.5745-7 2.7476-7
ALH           3.1367-6 1.9874-6 1.2235-6 7.2908-7 4.2072-7 2.3354-7 1.2436-7 6.3250-8 4.8026-8 2.1929-8
AR            2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 4.2827-1 4.2827-1
H             3.1308-6 2.0142-6 1.2587-6 7.6431-7 4.4974-7 2.5569-7 1.3997-7 7.3493-8 5.7885-8 2.7566-8
H2            4.5120-4 4.5234-4 4.5310-4 4.5359-4 4.5390-4 4.5409-4 4.5421-4 4.5427-4 7.1372-4 7.1376-4
NIAL(S)       3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 0.0000 0 0.0000 0
NI2AL3(S)     0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.8551-1 2.8551-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

AL(S)        NI(S)        NI(L)        NI           NI3AL(S)     NIAL3(S)

P, ATM        1.0000 0 1.0000 0 1.0000 0
T, DEG K          1273      1223      1173

AL(L)         2.8551-1 2.8551-1 2.8551-1
AL            9.1857-8 2.8019-8 7.7059-9
AR            4.2827-1 4.2827-1 4.2827-1
H             1.2395-8 5.2262-9 2.0493-9
H2            7.1377-4 7.1377-4 7.1378-4
NI2AL3(S)     2.8551-1 2.8551-1 2.8551-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

AL(S)        ALH          NI(S)        NI(L)        NI           NI3AL(S)     NIAL(S)      NIAL3(S)

P, ATM        1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
T, DEG K          2473      2423      2273      2123      2073      2023      1973      1923      1873      1823

AL(L)         0.0000 0 0.0000 0 0.0000 0 4.1230-1 4.5912-1 4.8742-1 5.0501-1 5.1604-1 3.5748-1 3.5998-1
AL            5.3295-1 5.3294-1 5.3292-1 1.2073-1 7.3936-2 4.5660-2 2.8093-2 1.7080-2 5.9651-3 3.4803-3
ALH           1.1525-4 1.3938-4 2.2619-4 1.2926-4 9.7359-5 7.1746-5 5.1711-5 3.6430-5 2.2683-5 1.5155-5
AR            1.9990-1 1.9991-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 2.7260-1 2.7260-1
H             4.6361-4 4.1574-4 2.5448-4 1.2421-4 9.3718-5 6.9260-5 5.0125-5 3.5507-5 2.2265-5 1.5005-5
H2            4.3753-5 5.5644-5 9.2898-5 2.0649-4 2.3768-4 2.6272-4 2.8230-4 2.9725-4 4.3186-4 4.3926-4
NI            2.6653-1 2.6654-1 2.6657-1 2.6658-1 2.6658-1 2.6658-1 2.6658-1 2.6658-1 4.9581-7 1.8446-7
NIAL(S)       0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 3.6347-1 3.6347-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

AL(S)        NI(S)        NI(L)        NI3AL(S)     NI2AL3(S)    NIAL3(S)

P, ATM        1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
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 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL(L)          3.6149-1 3.6238-1 3.6289-1 3.6317-1 3.6333-1 3.6340-1 3.6344-1 3.6346-1 2.8550-1 2.8551-1
 AL             1.9757-3 1.0869-3 5.7720-4 2.9472-4 1.4409-4 6.7137-5 2.9663-5 1.2357-5 7.5746-6 2.7476-6
 ALH            9.8767-6 6.2661-6 3.8612-6 2.3051-6 1.3294-6 7.3817-7 3.9316-7 1.9999-7 1.5186-7 6.9343-8
 AR             2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 4.2827-1 4.2827-1
 H              9.8834-6 6.3504-6 3.9725-6 2.4138-6 1.4211-6 8.0818-7 4.4251-7 2.3237-7 1.8303-7 8.7169-8
 H2             4.4446-4 4.4803-4 4.5042-4 4.5198-4 4.5296-4 4.5357-4 4.5392-4 4.5412-4 7.1361-4 7.1370-4
 NI             6.509 -8 2.165 -8 6.748 -9 1.957 -9 5.244-10 1.288-10 2.872-11 5.761-12 2.940-13 4.174-14
 NIAL(S)        3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 0.0000 0 0.0000 0
 NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.8551-1 2.8551-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          NI(S)          NI(L)           NI3AL(S)       NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1
 T, DEG K           1273     1223     1173

 AL(L)          2.8551-1 2.8551-1 2.8551-1
 AL             9.1857-7 2.8019-7 7.7059-8
 ALH            2.9712-8 1.1852-8 4.3613-9
 AR             4.2827-1 4.2827-1 4.2827-1
 H              3.9197-8 1.6527-8 6.4806-9
 H2             7.1374-4 7.1377-4 7.1378-4
 NI2AL3(S)      2.8551-1 2.8551-1 2.8551-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)          NI(S)          NI(L)          NI             NI3AL(S)       NIAL(S)        NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)          3.6511-1 4.3175-1 5.0431-1 5.2452-1 5.2749-1 5.2950-1 5.3084-1 5.3172-1
 AL             1.6783-1 1.0123-1 2.8752-2 8.5951-3 5.6347-3 3.6348-3 2.3001-3 1.4239-3
 ALH            2.1707-4 1.7903-4 9.1928-5 4.1080-5 3.0367-5 2.2044-5 1.5698-5 1.0954-5
 AR             1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1 1.9993-1
 H              2.1108-4 1.7344-4 8.8387-5 3.9475-5 2.9232-5 2.1281-5 1.5217-5 1.0677-5
 H2             1.1915-4 1.5699-4 2.4307-4 2.9295-4 3.0342-4 3.1156-4 3.1776-4 3.2241-4
 NI(L)          2.5429-1 2.5981-1 2.6516-1 2.6628-1 2.6641-1 2.6648-1 2.6652-1 2.6655-1
 NI             1.2294-2 6.7656-3 1.4203-3 2.9906-4 1.7225-4 9.6920-5 5.3084-5 2.8203-5
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          NI(S)          NI3AL(S)       NIAL(S)        NI2AL3(S)      NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL(L)          3.6307-1 3.6325-1 3.6335-1 3.6341-1 3.6344-1 3.6346-1 3.6347-1 3.6347-1 2.8551-1 2.8551-1
 AL             3.9286-4 2.1669-4 1.1524-4 5.8893-5 2.8805-5 1.3425-5 5.9322-6 2.4713-6 1.5149-6 5.4952-7
 ALH            4.4311-6 2.8086-6 1.7294-6 1.0319-6 5.9488-7 3.3024-7 1.7586-7 8.9447-8 6.7917-8 3.1012-8
 AR             2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 2.7260-1 4.2827-1 4.2827-1
 H              4.4341-6 2.8465-6 1.7793-6 1.0806-6 6.3591-7 3.6156-7 1.9794-7 1.0393-7 8.1860-8 3.8985-8
 H2             4.4991-4 4.5151-4 4.5258-4 4.5328-4 4.5372-4 4.5399-4 4.5415-4 4.5424-4 7.1370-4 7.1376-4
 NI             1.294 -8 4.317 -9 1.347 -9 3.911-10 1.048-10 2.575-11 5.744-12 1.152-12 5.879-14 8.347-15
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NIAL(S)         3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 3.6347-1 0.0000 0 0.0000 0
NI2AL3(S)       0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.8551-1 2.8551-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

AL(S)         NI(S)         NI(L)         NI3AL(S)      NIAL3(S)

P, ATM          5.0000-1 5.0000-1 5.0000-1
T, DEG K            1273     1223     1173

AL(L)           2.8551-1 2.8551-1 2.8551-1
AL              1.8371-7 5.6037-8 1.5412-8
ALH             1.3288-8 5.3006-9 1.9504-9
AR              4.2827-1 4.2827-1 4.2827-1
H               1.7530-8 7.3910-9 2.8982-9
H2              7.1376-4 7.1377-4 7.1378-4
NI2AL3(S)       2.8551-1 2.8551-1 2.8551-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

AL(S)         NI(S)         NI(L)         NI            NI3AL(S)      NIAL(S)       NIAL3(S)
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  REACTANTS
  AR   1.0000     0.0000     0.0000     0.0000     0.0000     3.000000  M      0.00      0.000      0.00000
  NI   1.0000     0.0000     0.0000     0.0000     0.0000     2.000000  M      0.00      0.000      0.00000
  H    2.0000     0.0000     0.0000     0.0000     0.0000     0.005000  M      0.00      0.000      0.00000
  AL   1.0000     0.0000     0.0000     0.0000     0.0000     5.000000  M      0.00      0.000      0.00000

  P, ATM        1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
  T, DEG K          2473      2423      2273      2123      2073      2023      1973      1923

  AL(L)         4.8837-1 4.9132-1 4.9657-1 4.9912-1 4.9933-1 4.9947-1 4.9957-1 4.9964-1
  AL            1.1280-2 8.3474-3 3.1394-3 6.1834-4 4.1116-4 2.6780-4 1.7057-4 1.0604-4
  ALH           1.0289-4 8.3015-5 4.1735-5 1.4190-5 1.0419-5 7.5219-6 5.3328-6 3.7082-6
  AR            2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1
  H             1.0005-4 8.1195-5 4.0127-5 1.3635-5 1.0030-5 7.2614-6 5.1692-6 3.6133-6
  H2            3.9828-4 4.1725-4 4.5882-4 4.[illegible]584-4 4.8953-4 4.9236-4 4.9450-4 4.9609-4
  NI(L)         0.0000 0 0.0000 0 0.0000 0 1.9988-1 1.9989-1 1.9989-1 1.9990-1 1.9990-1
  NI            1.9990-1 1.9990-1 1.9990-1 2.1515-5 1.2569-5 7.1408-6 3.9364-6 [illegible]1003-6
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI
 AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

 P, ATM        1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
 T, DEG K          1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

 AL(L)         3.7474-1 3.7475-1 3.7476-1 3.7476-1 3.7476-1 3.7477-1 3.7477-1 3.7477-1 3.3306-1 3.3306-1
 AL            2.6967-5 1.4083-5 7.9185-6 4.0474-6 1.9798-6 9.2275-7 4.0776-7 1.6987-7 8.8358-8 3.2051-8
 ALH           1.3664-6 8.6516-7 5.3233-7 3.1747-7 1.8296-7 1.0155-7 5.4071-8 2.7499-8 1.7717-8 8.0894-9
 AR            3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 4.9958-1 4.9958-1
 H             1.36[illegible]3-6 8.7681-7 5.4768-7 3.3244-7 1.9558-7 1.1118-7 6.0858-8 3.1952-8 2.1354-8 1.0169-8
 H2            6.2324-4 6.2374-4 6.2407-4 6.2428-4 6.2442-4 6.2453-4 6.2457-4 6.2459-4 8.3262-4 8.3263-4
 NIAL(S)       2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 0.0000 0 0.0000 0
 NI2AL3(S)     0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 1.6653-1 1.6653-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        NI(S)        NI(L)        NI           NI3AL(S)     NIAL3(S)

 P, ATM        1.0000 1 1.0000 1 1.0000 1
 T, DEG K          1273      1223      1173

 AL(L)         3.3306-1 3.3306-1 3.3306-1
 AL            1.072 -8 3.268 -9 8.989-10
 AR            4.9958-1 4.9958-1 4.9958-1
 H2            8.3264-4 8.3264-4 8.3264-4
 NI2AL3(S)     1.6653-1 1.6653-1 1.6653-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

AL(S)        ALH          H            NI(S)        NI(L)        NI           NI3AL(S)     NIAL(S)      NIAL3(S)
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 P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K            2473      2423      2273      2123      2073      2023      1973      1923

 AL(L)           4.1270-1 4.3977-1 4.7960-1 4.9340-1 4.9555-1 4.9703-1 4.9802-1 4.9867-1
 AL              8.6813-2 5.9785-2 2.0048-2 6.3049-3 4.1648-3 2.7004-3 1.7147-3 1.0639-3
 ALH             2.3441-4 1.9321-4 9.9822-5 4.3929-5 3.2422-5 2.3502-5 1.6716-5 1.1652-5
 AR              2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1 2.9985-1
 H               2.2793-4 1.8717-4 9..015-5 4.2213-5 3.1209-5 2.2688-5 1.6203-5 1.1357-5
 H2              2.6858-4 3.0957-4 4.0283-4 4.5668-4 4.6793-4 4.7666-4 4.8329-4 4.8825-4
 NI(L)           1.9354-1 1.9590-1 1.9891-1 1.9968-1 1.9977-1 1.9983-1 1.9986-1 1.9988-1
 NI              6.3592-3 3.9957-3 9.9034-4 2.1938-4 1.2731-4 7.2005-5 3.9573-5 2.1072-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)          NI(S)          NI3AL(S)       NIAL(S)        NI2AL3(S)      NIAL3(S)

 P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K            1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

 AL(L)           3.7449-1 3.7461-1 3.7468-1 3.7472-1 3.7475-1 3.7476-1 3.7476-1 3.7476-1 3.3305-1 3.3306-1
 AL              2.6985-4 1.4889-4 7.9200-5 4.0478-5 1.9799-5 9.2277-6 4.0776-6 1.6987-6 8.8358-7 3.2051-7
 ALH             4.3122-6 2.7323-6 1.6820-6 1.0034-6 5.7839-7 3.2106-7 1.709 -7 8.6954-8 5.6023-8 2.5581-8
 AR              3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 3.7477-1 4.9958-1 4.9958-1
 H               4.3151-6 2.7691-6 1.7305-6 1.0507-6 6.1828-7 3.5351-7 1.0243-7 1.0104-7 6.7524-8 3.2157-8
 H2              6.2030-4 6.2186-4 6.2290-4 6.2358-4 6.2401-4 6.2427-4 6.2443-4 6.2452-4 8.3258-4 8.3262-4



 NIAL(S)        2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 2.4984-1 0.0000 0 0.0000 0
 NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 1.6653-1 1.6653-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)          NI(S)          NI(L)          NI             NI3AL(S)       NIAL3(S)

 P, ATM         1.0000 0 1.0000 0 1.0000 0
 T, DEG K           1273      1223      1173

 AL(L)          3.3306-1 3.3306-1 3.3306-1
 AL             1.0735-7 3.2684-8 8.9891
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 REACTANTS
 AR  1.0000     0.0000     0.0000     0.0000     0.0000    1.000000  M       0.00       0.000       0.00000
 NI  1.0000     0.0000     0.0000     0.0000     0.0000    3.000000  M       0.00       0.000       0.00000
 H   2.0000     0.0000     0.0000     0.0000     0.0000    0.005000  M       0.00       0.000       0.00000
 AL  1.0000     0.0000     0.0000     0.0000     0.0000    2.000000  M       0.00       0.000       0.00000

 P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
 T, DEG K           2473      2423      2273      2123      2073      2023      1973      1923

 AL(L)          3.1786-1 3.2180-1 3.2881-1 3.3270-1 3.3282-1 3.3290-1 3.3296-1 3.3299-1
 AL             1.5039-2 1.1129-2 4.1855-3 3.4456-4 2.2911-4 1.4923-4 9.5044-5 5.9088-5
 ALH            1.5519-4 1.2611-4 6.2483-5 1.3754-5 1.0083-5 7.2705-6 5.1498-6 3.5785-6
 AR             1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H              1.5091-4 1.2217-4 6.0076-5 1.3217-5 9.7062-6 7.0186-6 4.9918-6 3.4879-6
 H2             6.7059-4 7.0850-4 7.7136-4 8.1915-4 8.2274-4 8.2549-4 8.2757-4 8.2911-4
 NI(L)          0.0000 0 0.0000 0 0.0000 0 4.9957-1 4.9958-1 4.9958-1 4.9958-1 4.9958-1
 NI             4.9958-1 4.9958-1 4.9958-1 1.1989-5 7.0038-6 3.9790-6 2.1935-6 1.1703-6
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        NI(S)         NI3AL(S)     NIAL(S)       NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
 T, DEG K           1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

 AL             5.030 -8 2.018 -8 8.014 -9 1.192 -8 4.382 -9 1.508 -9 4.821-10 1.422-10 3.836-11 9.365-12
 AR             2.4969-1 2.4969-1 2.4969-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              1.5817-6 1.0140-6 6.3326-7 5.1224-7 3.0133-7 1.7129-7 9.3757-8 4.9225-8 2.4678-8 1.1752-8
 H2             1.2476-3 1.2479-3 1.2482-3 1.6636-3 1.6638-3 1.6638-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI(S)          0.0000 0 2.4969-1 2.4969-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)          2.4969-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI             2.128 -7 9.772 -8 4.088 -8 7.244 -9 2.584 -9 8.598-10 2.651-10 7.508-11 1.936-11 4.499-12
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9938-1 4.9938-1 4.9938-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         ALH           NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K           2473      2423      2273      2123      2073      2023      1973      1923

 AL(L)          2.8439-1 2.9952-1 3.2178-1 3.2950-1 3.3070-1 3.3153-1 3.3208-1 3.3245-1
 AL             4.8410-2 3.3332-2 1.1174-2 3.5136-3 2.3209-3 1.5048-3 9.5550-4 5.9283-4
 ALH            2.5704-4 2.0581-4 9.9650-5 4.3141-5 3.1677-5 2.2872-5 1.6220-5 1.1283-5
 AR             1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H              2.4994-4 1.9938-4 9.5812-5 4.1456-5 3.0492-5 2.2080-5 1.5723-5 1.0997-5
 H2             5.7915-4 6.3005-4 7.3491-4 7.9034-4 8.0156-4 8.1016-4 8.1667-4 8.2150-4
 NI(L)          4.9604-1 4.9736-1 4.9903-1 4.9946-1 4.9951-1 4.9954-1 4.9956-1 4.9957-1
 NI             3.5461-3 2.2278-3 5.5198-4 1.2225-4 7.0947-5 4.0125-5 2.2052-5 1.1742-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)        NI(S)         NI3AL(S)     NIAL(S)       NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K           1773      1723      1673      1623      1573      1523      1473      1423      1373      1323
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 AL             5.030 -7 2.018 -7 8.014 -8 1.192 -7 4.382 -8 1.508 -8 4.821 -9 1.422 -9 3.836-10 9.365-11
 ALH            1.394 -8 6.415 -9 2.946 -9 5.113 -9 2.214 -9 9.072-10 3.496-10 1.259-10 4.206-11 1.292-11
 AR             2.4969-1 2.4969-1 2.4969-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              4.9983-6 3.2051-6 2.0020-6 1.6196-6 9.5282-7 5.4163-7 2.9648-7 1.5566-7 7.8037-8 3.7163-8
 H2             1.2459-3 1.2468-3 1.2474-3 1.6631-3 1.6635-3 1.6637-3 1.6638-3 1.6638-3 1.6639-3 1.6639-3
 NI(S)          0.0000 0 2.4969-1 2.4969-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)          2.4969-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI             2.128 -6 9.772 -7 4.088 -7 7.244 -8 2.584 -8 8.598 -9 2.650 -9 7.508-10 1.936-10 4.499-11
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9937-1 4.9937-1 4.9938-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)       AL(L)        NI2AL3(S)    NIAL3(S)


 P, ATM         1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AR             3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              1.671 -8 7.046 -9 2.763 -9 9.979-10 3.282-10 9.700-11 2.533-11 5.731-12 1.096-12 1.718-13 2.126-14
 H2             1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)       1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)       AL(L)        AL           ALH          NI(S)        NI(L)        NI           NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)          0.0000 0 0.0000 0 0.0000 0 2.8922-1 3.0631-1 3.1657-1 3.2292-1 3.2689-1
 AL             3.3274-1 3.3274-1 3.3272-1 4.3698-2 2.6645-2 1.6416-2 1.0087-2 6.1284-3
 ALH            1.6318-4 1.9319-4 2.9833-4 1.4246-4 1.0257-4 7.3203-5 5.1567-5 3.5739-5
 AR             1.6645-1 1.6647-1 1.6651-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H              1.0514-3 9.2297-4 5.3761-4 1.3690-4 9.8731-5 7.0667-5 4.9986-5 3.4834-5
 H2             2.2500-4 2.7426-4 4.1460-4 6.9296-4 7.3199-4 7.6071-4 7.8186-4 7.9735-4
 NI(L)          0.0000 0 0.0000 0 0.0000 0 4.9806-1 4.9877-1 4.9915-1 4.9935-1 4.9946-1
 NI             4.9936-1 4.9940-1 4.9952-1 1.5205-3 8.1451-4 4.3773-4 2.3280-4 1.2138-4
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDI

 AL(S)       NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)


 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL             5.031 -6 2.018 -6 8.014 -7 1.192 -6 4.382 -7 1.508 -7 4.821 -8 1.422 -8 3.836 -9 9.365-10
 ALH            4.398 -8 2.026 -8 9.308 -9 1.616 -8 7.000 -9 2.868 -9 1.105 -9 3.981-10 1.330-10 4.087-11
 AR             2.4968-1 2.4969-1 2.4969-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              1.5772-5 1.0122-5 6.3254-6 5.1189-6 3.0121-6 1.7124-6 9.3748-7 4.9223-7 2.4677-7 1.1752-7
 H2             1.2405-3 1.2434-3 1.2453-3 1.6613-3 1.6624-3 1.6630-3 1.6636-3 1.6637-3 1.6638-3 1.6639-3
 NI(S)          0.0000 0 2.4968-1 2.4968-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)          2.4967-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI             2.128 -5 9.772 -6 4.088 -6 7.244 -7 2.584 -7 8.598 -8 2.651 -8 7.508 -9 1.936 -9 4.499-10
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
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 NIAL(S)        4.9936-1 4.9937-1 4.9937-1 4.9916-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)         AL(L)          NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AR             3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              5 284 -8 2.228 -8 8.736 -9 3.156 -9 1.038 -9 3.067-10 8.011-11 1.812-11 3.466-12 5.434-13 6.723-14
 H2             1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)       1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9917-1 4.9917-1 4.9917-1 4 9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)         AL(L)          AL             ALH            NI(S)          NI(L)          NI             NI2AL3(S)    NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)          0.0000 0 6.5144-3 3.0888-1 3.2581-1 3.2830-1 3.2999-1 3.3111-1 3.3185-1
 AL             3.3259-1 3.2606-1 2.4037-2 7.1840-3 4.7094-3 3.0378-3 1.9223-3 1.1900-3
 ALH            4.4056-4 4.8400 4 1.4197-4 6 1000-5 4.4760-5 3.2311-5 2.2914-5 1.5941-5
 AR             1.6652-1 1 6653 1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1 1.6653-1
 H              5.6796-4 4.6888-4 1.3650-4 5 8617-5 4.3086-5 3.1192-5 2.2211-5 1.5537-5
 H2             3.2832-4 3.5621-4 6.9341-4 7 7283-4 7.8872-4 8.0089-4 8.1008-4 8.1690-4
 NI(L)          0.0000 0 0.0000 0 4.9840-1 4.9933-1 4.9944-1 4.9950-1 4.9954-1 4.9956-1
 NI             4.9955-1 4.9959-1 1.1874-3 2.4996-4 1.4396-4 8.1002-5 4.4364-5 2.3570-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)         NI(S)          NI3AL(S)       NIAL(S)        NI2AL3(S)    NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5 0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL             1.006 -6 4.036 -7 1.603 -7 2.384 -7 8.764 -8 3.015 -8 9.643 -9 2.845 -9 7.672-10 1.873-10
 ALH            1.970 -8 9.069 -9 4.166 -9 7.230 -9 3.132 -9 1.283 -9 4.944-10 1.780-10 5.948-11 1.828-11
 AR             2.4969-1 2.4969-1 2.4969-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              7.0658-6 4.5315-6 2.8307-6 2.2902-6 1.3474-6 7.6596-7 4.1928-7 2.2014-7 1.1036-7 5.2556-8
 H2             1.2449-3 1.2462-3 1.2470-3 1.6627-3 1.6634-3 1.6636-3 1.6637-3 1.6638-3 1.6639-3 1.6639-3
 NI(S)          0.0000 0 2.4969-1 2.4969-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)          2.4968-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI             4.256 -6 1.954 -6 8.175 -7 1.449 -7 5.168 -8 1.720 -8 5.301 -9 1.502 -9 3.873-10 8.999-11
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9937-1 4.9937-1 4.9937-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)         AL(L)          NI2AL3(S)    NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AR             3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              2.363 -8 9.964 -9 3.907 -9 1.411 -9 4.642-10 1.372-10 3.582-11 8.105-12 1.550-12 2.430-13 3.007-14
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 H2            1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)      1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)       4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E 07 FOR ALL ASSIGNED CONDITIO

 AL(S)      AL(L)       AL          ALH         NI(S)       NI(L)       NI          NI2AL3(S)   NIAL3(S)

 P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL            3.3278-1 3.3278-1 3.3278-1 3.3281-1 3.3283-1 3.3285-1 3.3287-1 3.3290-1 3.8195-4 1.2066-3
 ALH           2.5616-6 3.4396-6 8.7876-6 2.2815-5 3.0534-5 3.9849-5 5.0597-5 6.2611-5 1.6641-7 8.7518-7
 AR            1.6639-1 1.6639-1 1.6640-1 1.6642-1 1.6643-1 1.6645-1 1.6646-1 1.6648-1 2.4954-1 2.4936-1
 H             1.6503-3 1.6431-3 1.5833-3 1.3533-3 1.2072-3 1.0295-3 8.3622-4 6.4697-4 4.5828-4 2.3183-4
 H2            5.5437-6 8.6916-6 3.5959-5 1.4405-4 2.1330-4 2.9754-4 3.8890-4 4.7761-4 1.0185-3 1.1304-3
 NI(L)         0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 2.4599-1
 NI            4.9917-1 4.9917-1 4.9919-1 4.9925-1 4.9929-1 4.9934-1 4.9939-1 4.9944-1 2.4992-1 4.5772-3
 NIAL(S)       0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9869-1 4.9751-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)      AL(L)       NI(S)       NI3AL(S)    NI2AL3(S)   NIAL3(S)

 P, ATM        1.0000-3 1.0000-3 1.0000-3 1 0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K          1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL            5.0819-4 2.0273-4 8.0293-5 1 1926-4 4.3830-5 1.5078-5 4.8216-6 1.4223-6 3.8362-7 9.3649-8
 ALH           4.294 -7 1.993 -7 9.210 -8 1.605 -7 6.972 -8 2.862 -8 1.104 -8 3.978 -9 1.330 -9 4.086-10
 AR            2.4954-1 2.4962-1 2.4966-1 3.3275-1 3.3277-1 3.3277-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             1.5399-4 9.9591-5 6.2591-5 5.0845-5 3.0000-5 1.7085-5 9.3627-6 4.9189-6 2.4669-6 1.1750-6
 H2            1.1705-3 1.1982-3 1.2170-3 1.6382-3 1.6488-3 1.6553-3 1.6592-3 1.6614-3 1.6627-3 1.6633-3
 NI(S)         0.0000 0 2.4885-1 2.4933-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)         2.4790 1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI            2.1501-3 9.8174-4 4.0957-4 7.2475-5 2.5843-5 8.5988-6 2.6506-6 7.5082-7 1.9365-7 4.4994-8
 NI3AL(S)      0.0000 0 0.0000 0 0.0000 0 1.6640-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)       4.9857-1 4.9905-1 4.9924-1 4.9898-1 4.9909-1 4.9914-1 4.9916-1 4.9916-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)      AL(L)       NI2AL3(S)   NIAL3(S)

 P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K          1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AL            2.045 -8 3.941 -9 6.595-10 9.405-11 1.118-11 1.078-12 8.171-14 4.679-15 1.930-16 5.398-18 9.501-20
 AR            3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H             5.204 -7 2.228 -7 8.736 -8 3.156 -8 1.038 -8 3.067 -9 8.011-10 1.812-10 3.466-11 5.434-12 6.723-13
 H2            1.6636-3 1.6639-3 1.6639-3 1 6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)      1.6639-1 1.6639-1 1.6639-1 1 6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)       4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E 07 FOR ALL ASSIGNED CONDI

 AL(S)      AL(L)       ALH         NI(S)       NI(L)       NI          NI2AL3(S)   NIAL3(S)

 P, ATM        1.0000-6 1.0000-6 1.0000-6 1 0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923     1873     1823
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 AL             3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 ALH            2.5828-9 3.4831-9 9.2346-9 2.8042-8 4.2061-8 6.4327-8 1.0046-7 1.6035-7 2.6176-7 4.3657-7
 AR             1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 H              1.6639-3 1.6639-3 1.6638-3 1.6634-3 1.6631-3 1.6623-3 1.6607-3 1.6575-3 1.6504-3 1.6346-3
 H2             5.6357-9 8.9129-9 3.9712-8 2.1764-7 4.0487-7 7.7569-7 1.5339-6 3.1347-6 6.6218-6 1.4416-5
 NI             4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9918-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)         AL(L)          NI(S)          NI(L)          NI3AL(S)      NIAL(S)        NI2AL3(S)    NIAL3(S)


 P, ATM         1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323


 AL             3.3279-1 3.3280-1 3.3283-1 2.3901-1 5.3648-2 1.6084-2 4.9197-3 1.4307-3 3.8423-4 9.3687-5
 ALH            7.4038-7 1.2604-6 2.0999-6 4.6413-6 2.0530-6 8.5714-7 3.3711-7 1.2329-7 4.1598-8 1.2855-8
 AR             1.6639-1 1.6640-1 1.6641-1 2.8420-1 3.2211-1 3.2964-1 3.3183-1 3.3250-1 3.3270-1 3.3276-1
 H              1.5992-3 1.5217-3 1.3692-3 1.4703-3 8.8333-4 5.1171-4 2.8588-4 1.5244-4 7.7180-5 3.6962-5
 H2             3.2005-5 7.0526-5 1.4642-4 6.8354-4 1.1678-3 1.3919-3 1.5160-3 1.5862-3 1.6249-3 1.6453-3
 NI             4.9918-1 4.9920-1 4.9924-1 1.4525-1 3.1632-2 9.1730-3 2.7045-3 7.5527-4 1.9396-4 4.5012-5
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 1.8898-1 1.7206-1 1.6828-1 1.6702-1 1.6659-1 1.6645-1 1.6640-1
 NIAL(S)        0.0000 0 0.0000 0 0.0000 0 1.4040-1 4.1850-1 4.7492-1 4.9172-1 4.9698-1 4.9857-1 4.9902-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)         AL(L)          NI(S)          NI(L)          NI2AL3(S)     NIAL3(S)


 P, ATM         1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773


 AL             2.045 -5 3.941 -6 6.595 -7 9.405 -8 1.118 -8 1.078 -9 8.171-11 4.679-12 1.930-13 5.398-15 9.501-17
 AR             3.3277-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              1.667 -5 7.038 -6 2.762 -6 9.977 -7 3.282 -7 9.700 -8 2.533 -8 5.731 -9 1.096 -9 1.718-10 2.126-11
 H2             1.6555-3 1.6604-3 1.6625-3 1.6634-3 1.6637-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI             9.304 -6 1.687 -6 2.640 -7 3.494 -8 3.822 -9 3.358-10 2.292-11 1.167-12 4.212-14 1.012-15 1.498-17
 NI3AL(S)       1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 NIAL(S)        4.9913-1 4.9916-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

 AL(S)         AL(L)          ALH            NI(S)          NI(L)          NI2AL3(S)     NIAL3(S)
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AR  1.0000     0.0000      0.0000      0.0000      0.0000     1.000000  M
NI  1.0000     0.0000      0.0000      0.0000      0.0000     5.000000  M       0.00        0.000        0.00000
H   2.0000     0.0000      0.0000      0.0000      0.0000     0.005000  M       0.00        0.000        0.00000
AL  1.0000     0.0000      0.0000      0.0000      0.0000     2.000000  M       0.00        0.000        0.00000

P, ATM          1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
T, DEG K           2473      2423      2273      2123      2073      2023      1973      1923

AL(L)           2.3279-1 2.3721 1 2.4508-1 2.4958-1 2.4966-1 2.4973-1 2.4977-1 2.4980-1
AL              1.6915-2 1.2517-2 4.7077-3 2.5848-4 1.7107 4 1.1194-4 7.1298-5 4.4325-5
ALH             1.3935-4 1.1376 4 5.6904 5 1.0318-5 7.5641-6 5.4540-6 3.8631-6 2.6845-6
AR              1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1
H               1.3551-4 1.1021-4 5.4712-5 9.9145-6 7.2812-6 5.2651-6 3.7447-6 2.6165-6
H2              4.8718-4 5.1262-4 5.6880-4 6.1449-4 6.1719-4 6.1925-4 6.2081-4 6.2196-4
NI(L)           0.0000 0 0.0000 0 0.0000 0 6.2460-1 6.2460-1 6.2461-1 6.2461-1 6.2461-1
NI              6.2461-1 6.2461-1 6.2461-1 8.9936-6 5.2539-6 2.9849-6 1.6455-6 8.7794-7
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

P, ATM          1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1 1.0000 1
T, DEG K           1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

AL              3.355 -8 1.346 -8 5.345 -9 1.192 -8 4.382 -9 1.508 -9 4.821-10 1.422-10 3.836-11 9.365-12
AR              1.6653-1 1.6653-1 1.6653-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
H               1.0549-6 6.7627-7 4.2235-7 5.1224-7 3.0133-7 1.7129-7 9.3757-8 4.9225-8 2.4678-8 1.1752-8
H2              8.3211-4 8.3230-4 8.3246-4 1.6636-3 1.6638-3 1.6638-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
NI(S)           0.0000 0 4.9958-1 4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
NI(L)           4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
NI              1.419 -7 6.517 -8 2.726 -8 7.244 -9 2.584 -9 8.598-10 2.651-10 7.508-11 1.936-11 4.499-12
NI3AL(S)        0.0000 0 0.0000 0 0.0000 0 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
NIAL(S)         3.3306-1 3.3306-1 3.3306-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

AL(S)        AL(L)        ALH          NI2AL3(S)    NIAL3(S)

P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
T, DEG K           2473      2423      2273      2173      2073      2023      1973      1923

AL(L)           2.1334-1 2.2469-1 2.4139-1 2.4718-1 2.4808-1 2.4870-1 2.4911-1 2.4939-1
AL              3.6315-2 2.5004-2 8.3822-3 2.6357-3 1.7410-3 1.1288-3 7.1677-4 4.4471-4
ALH             1.9282-4 1.5439-4 7.4753 5 3.2363-5 2.3763-5 1.7158-5 1.2168-5 8.4639-6
AR              1.2492-1 1.2492 1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1
H               1.8749-4 1.4956-4 7.1874-5 3.1098 5 2.2874-5 1.6563-5 1.1795-5 8.2495-6
H2              4.3445-4 4.7263-4 5.5130-4 5.9288-4 6.0129-4 6.0775-4 6.1263-4 6.1625-4
NI(L)           6.2195-1 6.2294-1 6.2420-1 6.2452-1 6.2456-1 6.2458-1 6.2459-1 6.2460-1
NI              2.6601-3 1.6712-3 4.1407 4 9.1710-5 5.3221-5 3.0100-5 1.6542-5 8.8083-6
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

P, ATM          1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0 1.0000 0
T, DEG K           1773      1723      1673      1623      1573      1523      1473      1423      1373      1323

AL              3.355 -7 1.346 -7 5.345 -8 1.192 -7 4.382 -8 1.508 -8 4.821 -9 1.422 -9 3.836-10 9.365-11
AR              1.6653-1 1.6653-1 1.6653-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
H               3.3336-6 2.1376-6 1.3352-6 1.6196-6 9.5282-7 5.4163-7 2.9648-7 1.5566-7 7.8037-8 3.7163-8
H2              8.3097-4 8.3157-4 8.3197-4 1.6631-3 1.6635-3 1.6637-3 1.6638-3 1.6638-3 1.6639-3 1.6639-3
NI(S)           0.0000 0 4.9958-1 4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
NI(L)           4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
NI              1.419 -6 6.517 -7 2.726 -7 7.244 -8 2.584 -8 8.598 -9 2.650 -9 7.538-10 1.936-10 4.499-11
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 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)        3.3305-1 3.3306-1 3.3306-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

 AL(S)        AL(L)        ALH          NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000-1 1.0000 1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)          0.0000 0 0.0000 0 2.2473-2 2.1696-1 2.2978-1 2.3747-1 2.4224-1 2.4522-1
 AL             2.4965-1 2.4959-1 2.2707-1 3.2781-2 1.9988-2 1.2315-2 7.5670-3 4.5972-3
 ALH            9.9344-5 2.0868-4 3.0083-4 1.0687-4 7.6942-5 5.4913-5 3.8683-5 2.6810-5
 AR             1.2487-1 1.2490-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1
 H              8.5311-4 5.6057-4 2.8924-4 1.0269-4 7.4064-5 5.3011-5 3.7497-5 2.6131-5
 H2             1.4815-4 2.3987-4 3.2958-4 5.1983-4 5.4911-4 5.7065-4 5.8652-4 5.9814-4
 NI(L)          0.0000 0 5.7824-1 6.1340-1 6.2347-1 6.2400-1 6.2428-1 6.2444-1 6.2452-1
 NI             6.2437-1 4.6256-2 1.1217-2 1.1406-3 6.1101-4 3.2836-4 1.7464-4 9.1056-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)        NI(S)        NI3AL(S)     NIAL(S)      NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL             3.355 -6 1.346 -6 5.345 -7 1.192 -6 4.382 -7 1.508 -7 4.821 -8 1.422 -8 3.836 -9 9.365-10
 ALH            2.933 -8 1.351 -8 6.208 -9 1.616 -8 7.000 -9 2.868 -9 1.105 -9 3.981-10 1.330-10 4.087-11
 AR             1.6653-1 1.6653-1 1.6653-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              1.0519-5 6.7506-6 4.2187-6 5.1189-6 3.0171-6 1.7124-6 9.3748-7 4.9223-7 2.4677-7 1.1752-7
 H2             8.2736-4 8.2925-4 8.3052-4 1.6613-3 1.6624-3 1.6630-3 1.6636-3 1.6637-3 1.6638-3 1.6639-3
 NI(S)          0.0000 0 4.9958-1 4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)          4.9957-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI             1.420 -5 6.518 -6 2.726 -6 7.244 -7 2.584 -7 8.598 -8 2.651 -8 7.508 -9 1.936 -9 4.499-10
 NI3AL(S)       0.0000 0 0.0000 0 0.0000 0 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)        3.3305-1 3.3305-1 3.3305-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)        AL(L)        NI2AL3(S)    NIAL3(S)

 P, ATM         1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1 1.0000-1
 T, DEG K           1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AR             3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H              5.284 -8 2.228 -8 8.736 -9 3.156 -9 1.038 -9 3.067-10 8.011-11 1.812-11 3.466-12 5.434-13 6.723-14
 H2             1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)       4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)        1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)        AL           ALH          NI(S)        NI(L)        NI           NI2AL3(S)    NIAL3(S)

 P, ATM         5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K           2473     2423     2273     2123     2073     2023     1973     1923

 AL(L)          0.0000 0 0.0000 0 2.3171-1 2.4441-1 2.4628-1 2.4754-1 2.4838-1 2.4894-1
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 AL              2.4954-1 2.4952-1 1.8031-2 5.3891-3 3.5328-3 2.2788-3 1.4420-3 8.9268-4
 ALH             2.8275-4 3.1754-4 1.0650-4 4.5760-5 3.3577-5 2.4238-5 1.7189-5 1.1958-5
 AR              1.2491-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1 1.2492-1
 H               4.8585-4 4.0462-4 1.0240-4 4.3972-5 3.2321-5 2.3399-5 1.6662-5 1.1655-5
 H2              2.4025-4 2.6354-4 5.2016-4 5.7974-4 5.9166-4 6.0079-4 6.0768-4 6.1280-4
 NI(L)           0.0000 0 0.0000 0 6.2372-1 6.2442-1 6.2450-1 6.2455-1 6.2458-1 6.2459-1
 NI              6.2455-1 6.2458-1 8.9072-4 1.8751-4 1.0799-4 6.0764-5 3.3280-5 1.7681-5
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)        NI(S)         NI3AL(S)      NIAL(S)       NI2AL3(S)    NIAL3(S)


 P, ATM          5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K            1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL              6.710 -7 2.692 -7 1.069 -7 2.384 -7 8.764 -8 3.015 -8 9.643 -9 2.845 -9 7.672-10 1.873-10
 ALH             1.314 -8 6.049 -9 2.778 -9 7.230 -9 3.132 -9 1.283 -9 4.944-10 1.780-10 5.948-11 1.828-11
 AR              1.6653-1 1.6653-1 1.6653-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H               4.7125-6 3.0223-6 1.8880-6 2.2902-6 1.3474-6 7.6596-7 4.1928-7 2.2014-7 1.1036-7 5.2556-8
 H2              8.3027-4 8.3112-4 8.3169-4 1.6627-3 1.6634-3 1.6636-3 1.6637-3 1.6638-3 1.6639-3 1.6639-3
 NI(S)           0.0000 0 4.9958-1 4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI(L)           4.9958-1 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI              2.839 -6 1.303 -6 5.452 -7 1.449 -7 5.168 -8 1.720 -8 5.301 -9 1.502 -9 3.873-10 8.999-11
 NI3AL(S)        0.0000 0 0.0000 0 0.0000 0 4.9917-1 4.9917 1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)         3.3305-1 3.3305-1 3.3306-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIO

 AL(S)        AL(L)         NI2AL3(S)    NIAL3(S)


 P, ATM          5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1 5.0000-1
 T, DEG K            1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AR              3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
 H               2.363 -8 9.964 -9 3.907 -9 1.411 -9 4.642-10 1.372-10 3.582-11 8.105-12 1.550-12 2.430-13 3.007-14
 H2              1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3 1.6639-3
 NI3AL(S)        4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 NIAL(S)         1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         AL            ALH           NI(S)         NI(L)         NI            NI2AL3(S)    NIAL3(S)


 P, ATM          1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
 T, DEG K            2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL              2.4969-1 2.4969-1 2.4969-1 2.4970-1 2.4971-1 2.4972-1 2.4973-1 2.4974-1 1.8494-3 8.0508-4
 ALH             1.4450-6 1.9424-6 5.0057-6 1.3393-5 1.8225-5 2.4218-5 3.1285-5 3.9292-5 1.1430-6 5.8395-7
 AR              1.2484-1 1.2484-1 1.2485-1 1.2486-1 1.2486-1 1.2487-1 1.2488-1 1.2489-1 1.6620-1 1.6638-1
 H               1.2407-3 1.2367-3 1.2020-3 1.0588-3 9.6039-4 8.3399-4 6.8919-4 5.4120-4 2.2735-4 1.5469-4
 H2              3.1337-6 4.9235-6 2.0726-5 8.0102-5 1.3501-4 1.9525-4 2.6417-4 3.3421-4 7.1676-4 7.5427-4
 NI(L)           0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9414-1 4.9689-1
 NI              6.2422-1 6.2422-1 6.2424-1 6.2428-1 6.2432-1 6.2436-1 6.2440-1 6.2445-1 6.3119-3 3.0541-3
 NIAL(S)         0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 3.3055-1 3.3196-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)        AL(L)         NI(S)         NI3AL(S)      NI2AL3(S)    NIAL3(S)
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NI2AL3(S)      0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

  AL(S)         NI(S)         NI(L)         NI3AL(S)      NIAL3(S)

  P, ATM        5.0000-1 5.0000-1 5.0000-1
  T, DEG K          1273     1223     1173

  AL(L)         0.0000 0 0.0000 0 5.1480-8
  AL            4.9198-8 4.7751-8 1.8008-8
  AR            4.9875-1 4.9875-1 4.9875-1
  H             3.5419-8 1.4933-8 5.8557-9
  H2            2.4937-3 2.4938-3 2.4938-3
  NI2AL3(S)     4.9875-1 4.9875-1 4.9875-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

  AL(S)         ALH           NI(S)         NI(L)         NI            NI3AL(S)      NIAL(S)       NIAL3(S)

  P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
  T, DEG K          2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

  AL            4.9917-1 4.9917-1 4.9918-1 4.9922-1 4.9925-1 4.9928-1 4.9932-1 4.9935-1 2.4983-1 2.4960-1
  ALH           3.8395-6 5.1541-6 1.3148-5 3.4025-5 4.5470-5 5.9252-5 7.5116-5 9.2806-5 1.0628-4 1.2378-4
  AR            1.6639-1 1.6639-1 1.6640-1 1.6642-1 1.6643-1 1.6645-1 1.6647-1 1.6648-1 2.4955-1 2.4964-1
  H             1.6490-3 1.6414-3 1.5793-3 1.3454-3 1.1984-3 1.0205-3 8.2763-4 6.3930-4 4.4743-4 3.0945-4
  H2            5.5352-6 8.6739-6 3.5778-5 1.4238-4 2.1022-4 2.9236-4 3.8095-4 4.6636-4 9.7089-4 1.0316-3
  NI            3.3278-1 3.3278-1 3.3280-1 3.3284-1 3.3286-1 3.3290-1 3.3293-1 3.3296-1 3.8204-4 8.4340-5
  NIAL(S)       0.0000 0 0.0000 0 0.0000 0 0.0000 0 0 0000 0 0.0000 0 0.0000 0 0.0000 0 4.9872-1 4.9920-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

  AL(S)         AL(L)         NI(S)         NI(L)         NI3AL(S)      NI2AL3(S)     NIAL3(S)

  P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
  T, DEG K          1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

  AL(L)         0.0000 0 8.4650-2 1.0252-1 2.1932-1 2.3569-1 2.4335-1 2.4693-1 2.4854-1 0.0000 0 0.0000 0
  AL            2.4955-1 1.6492-1 6.7099-2 3.0329-2 1.3972-2 6.3240-3 2.7557-3 1.1407-3 2.9374-5 8.7845-6
  ALH           1.4366-4 1.2232-4 6.7385-5 3.8249-5 2.1538-5 1.1827-5 6.2677-6 3.1815-6 1.0180-7 3.8331-8
  AR            2.4968-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 2.4969-1 4.9872-1 4.9874-1
  H             2.0718-4 1.2397-4 6.9328-5 4.0053-5 2.3024-5 1.2949-5 7.0545-6 3.6967-6 3.6971-6 1.7610-6
  H2            1.0730-3 1.1253-3 1.1801-3 1.2093-3 1.2262-3 1.2361-3 1.2418-3 1.2450-3 2.4917-3 2.4928-3
  NI            1.708 -5 3.286 -6 7.845 -7 2.014 -7 5.085 -8 1.213 -8 2.668 -9 5.318-10 5.681 -9 1.077 -9
  NIAL(S)       4.9933-1 4.9937-1 4.9937-1 4.9937-1 4.9938-1 4.9938-1 4.9938-1 4.9938-1 5.8823-5 1.7535-5
  NI2AL3(S)     0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.9869-1 4.9874-1
 ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDIT

  AL(S)         NI(S)         NI(L)         NI3AL(S)      NIAL3(S)

  P, ATM        1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3 1.0000-3
  T, DEG K          1273     1223     1173     1123     1073     1023      973      923      873      823      773

  AL            2.385 -6 5.809 -7 1.252 -7 9.124 -8 6.079 -8 4.743 -8 6.563 -9 7.302-10 6.292-11 4.007-12 1.779-13
  ALH           1.334 -8 4.249 -9 1.225 -9 1.226 -9 1.155 -9 1.317 -9 2.771-10 4.901-11 7.078-12 8.039-13 6.854-14
  AR            4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
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 H          7.919 -7 3.339 -7 1.309 -7 4.729 -8 1.556 -8 4.597 -9 1.201 -9 2.716-10 5.194-11 8.144-12 1.008-12
 H2         2.4934-3 2.4936-3 2.4937-3 2.4937-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3
 NIAL(S)    4.6860-6 1.0511-6 1.1257-7 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI2AL3(S)  4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 NIAL3(S)   0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 5.5969-9 6.8305-8 4.2268-8 3.7637-8 3.6979-8 3.6907-8
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIONS

 AL(S)         AL(L)         NI(S)         NI(L)         NI            NI3AL(S)

 P, ATM     1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K       2473     2423     2273     2123     2073     2023     1973     1923     1873     1823

 AL         4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1 4.9917-1
 ALH        3.8741-9 5.2246-9 1.3852-8 4.2[illegible]3-8 6.3091-8 9.6489-8 1.5068-7 2.4051-7 3.9261-7 6.5477-7
 AR         1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1 1.6639-1
 H          1.6639-3 1.6639-3 1.6638-3 1.6634-3 1.6631-3 1.6622-3 1.6607-3 1.6574-3 1.6503-3 1.6344-3
 H2         5.6357-9 8.9129-9 3.9712-8 2.1764-7 4.0486-7 7.7566-7 1.5338-6 3.1344-6 6.6207-6 1.4413-5
 NI         3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1 3.3278-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITION

 AL(S)         AL(L)         NI(S)         NI(L)         NI3AL(S)      NIAL(S)       NI2AL3(S)     NIAL3(S)

 P, ATM     1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K       1773     1723     1673     1623     1573     1523     1473     1423     1373     1323

 AL         4.9918-1 4.9920-1 4.9924-1 3.2530-1 2.5745-1 2.5049-1 2.4973-1 2.4966-1 2.9372-2 8.7844-3
 ALH        1.1103-6 1.8899-6 3.1481-6 5.4735-6 7.3335-6 9.4687-6 1.2004-5 1.5090-5 3.0858-6 1.1947-6
 AR         1.6639-1 1.6640-1 1.6641-1 2.2432-1 2.4697-1 2.4933-1 2.4962-1 2.4967-1 4.6943-1 4.8998-1
 H          1.5989-3 1.5212-3 1.3685-3 1.2393-3 8.2956-4 5.1119-4 2.9434-4 1.5911-4 1.1206-4 5.4888-5
 H2         3.1992-5 7.0477-5 1.4626-4 4.9922-4 8.1638-4 9.8634-4 1.0950-3 1.1612-3 2.2896-3 2.4218-3
 NI         3.3279-1 3.3280-1 3.3283-1 1.0098-1 1.0492-2 1.1683-3 1.1477-4 9.5860-6 5.6804-6 1.0774-6
 NIAL(S)    0.0000 0 0.0000 0 0.0000 0 3.4766-1 4.8344-1 4.9750-1 4.9913-1 4.9933-1 5.8732-2 1.7568-2
 NI2AL3(S)  0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 4.4006-1 4.8119-1
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITIC

 AL(S)         AL(L)         NI(S)         NI(L)         NI3AL(S)      NIAL3(S)

 P, ATM     1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6 1.0000-6
 T, DEG K       1273     1223     1173     1123     1073     1023      973      923      873      823      773

 AL         2.385 -3 5.809 -4 1.252 -4 2.348 -5 3.760 -6 5.021 -7 5.536 -8 5.524 -8 5.517 -8 4.007 -9 1.779-10
 ALH        4.198 -7 1.342 -7 3.872 -8 9.975 -9 2.258 -9 4.409-10 7.390-11 1.173-10 1.963-10 2.542-11 2.167-12
 AR         4.9637-1 4.9817-1 4.9863-1 4.9873-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 H          2.492 -5 1.054 -5 4.138 -6 1.495 -6 4.919 -7 1.454 -7 3.797 -8 8.589 -9 1.643 -9 2.575-10 3.187-11
 H2         2.4692-3 2.4855-3 2.4910-3 2.4929-3 2.4935-3 2.4937-3 2.4937-3 2.4938-3 2.4938-3 2.4938-3 2.4938-3
 NI         1.792 -7 2.571 -8 3.124 -9 3.144-10 2.552-11 1.620-12 7.533-14 6.418-17 2.418-20 1.772-22 8.605-25
 NIAL(S)    4.7702-3 1.1619-3 2.5034-4 4.6871-5 7.4084-6 8.9342-7 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0
 NI2AL3(S)  4.9398-1 4.9759-1 4.9850-1 4.9871-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1 4.9875-1
 NIAL3(S)   0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 9.6344-8 4.2574-8
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  0.10000E-07 FOR ALL ASSIGNED CONDITI

 AL(S)         AL(L)         NI(S)         NI(L)         NI3AL(S)
NIIAL1   OUT    15113   1-01-80   5:35a
NIIAL2   OUT    11730   1-01-80   5:43a
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THE DEVELOPMENT OF PLASMA SYNTHESIS TO PRODUCE PRE-ALLOYED, ULTRAFINE INTERMETALLIC ALUMINIDE POWDERS FOR INJECTION MOLDING -
James C. Withers, Sumit Guha, and R. O. Loutfy
Materials and Electrochemical Research Corp.
Tucson, AZ 85706

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Intermetallics offer significant potential in a variety of military applications. Current processing does not produce significantly small particle sizes to permit the injection molding of complex geometry components. In this Phase I program, the processes of gas phase plasma reaction and plasma initiated SHS reactions (PSHS) were investigated to produce small (<5 um) intermetallic particles suitable for injection molding. The gas plasma reaction process failed to produce intermetallic powders with a precise stoichiometric control. By contrast, the PSHS process was successful in producing fine (≤5 um size), irregular shaped powders of NiAl with excellent control of composition. Both stoichiometry control and capability of alloying with ternary additions were demonstrated for the PSHS process and molded powders were sintered to >96% density density in preliminary test which provides the basis for a proposed scale-up under a Phase II program. The PSHS process can be projected to produce particles at attractive economics of $10-50/lb. A novel process termed Cathode Arc transport (CAT) was demonstrated to produce ultra-fine (300-500 nm) spherical intermetallic powders. Excellent compositional control was demonstrated in the CAT transfer process to produce alloy powder. Nanometer intermetallic particles offer significant promise to microstructural control to achieve unusual and enhanced mechanical properties.

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