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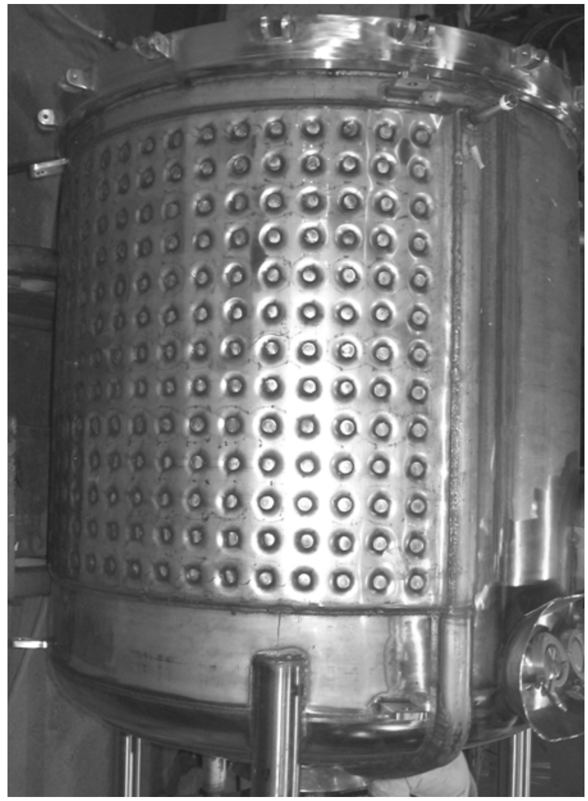
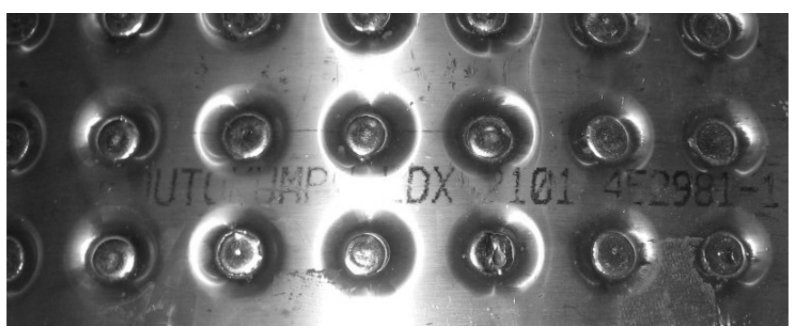
Duplex LDX 2101® (UNS# S32101) Stainless Steel for Tank and Vessel Thermal Dimple Jackets:

Advantages over Austenitic types 304, 304L, & 316L Stainless Steels:



- Stress Corrosion Cracking (SCC) better than 304 and 316L {See Section III}
- Chloride Pitting and Crevice corrosion resistance better than 304 and equal or better than 316L {See Section III}
- Higher Strength, similar to Alloy 625 (N06625) & Alloy 600 (N06600) {See Section IV}
- Better Thermal Shock Resistance (Low-Cycle Fatigue resistance) {See Section IV}
- Better High-Cycle Fatigue resistance {See Section V}
- Low Coefficient of Thermal Expansion, very similar to Alloy 625 (N06625) & Alloy 600 (N06600)
- Superior weld properties when ER2209 filler is used vs. ER316L when welding onto 304, 304L, and 316L (ultimate strength, fatigue resistance, acceptable microstructures and ferrite levels are achieved-See Section VI)
- Proof Tested producing ASME ratings higher than austenitic 304 and 316L stainless steels
- Competitively priced to types 304, 304L, and 316L stainless steels
- A cost effective alternative to Duplex 2205 (S31803/S32205), Alloy 600 (N06600) and Alloy 625 (N06625)
- LDX 2101® (S32101) is covered under ASME Pressure Vessel and Boiler Code Case 2418 for use in ASME Section VIII, Division 1 applications such as Appendix 17 Dimple Jackets
- Specifications:
  - UNS# S32101
  - EN 1.4162
  - ASME
    - SA-240, SA-182, SA-479, SA-789, SA-790



LDX 2101® is an Outokumpu Stainless Trademark

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I. Dimple Jacket (DJ) Design Background

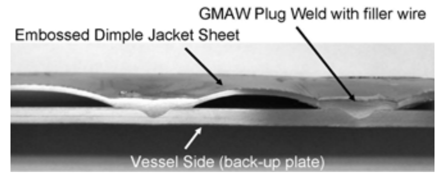

Figure 1-Typical Dimple Jacket Cross Section View

For years, dimple jackets on tanks and vessels for high purity applications such as the pharmaceutical, biotech, food, dairy, and beverage industries have been constructed from 304 and 316L stainless steel. Normally they are built to ASME Section VIII, Division 1, Appendix 17 {17-1(a)1 and 17-1(b)(3)} and built from 16ga sheet. (See figure 1.) When failures have occurred in the past, either from corrosion or fatigue, the simple fix of using thicker (14ga) 304, 304L or 316L was implemented, generally with limited success. Closer dimple plug weld spacing has also been attempted with limited success, as it possibly may add more stress risers and strain than the strength actually gained so it is not considered a solution. Stainless Steels 304, 304L and 316L are particularly susceptible to Stress Corrosion Cracking (SCC) and fatigue. The use of nickel Alloy 600 (N06600) and Alloy 625 (N06625) usually remedied the failures since they have reduced thermal stresses due to lower coefficients of thermal expansion, high strength, and their excellent resistance to SCC, however it is also very expensive. LDX 2101® (S32101) is a cost effective option for both the stainless and nickel alloys.

II. Common Dimple Jacket Failure Modes

Failures normally occur due to improper use, improper installation, improper weld process, improper material of construction, improper design, or a combination of the above. The most common modes of failures for dimple jackets are:

- Stress Corrosion Cracking (SCC) usually from chlorinated water or chlorides in insulation
- Chloride Pitting and Crevice corrosion
- Thermal Shocking (Low-Cycle Fatigue)
- High-Cycle Fatigue

LDX 2101® (S32101) exceeds 304, 304L, and 316L in these common failure areas and are addressed in this data sheet.

III. Corrosion Resistance Data

Resistances to pitting are improved with additives of chrome, molybedenum, and nitrogen. Pitting attack normally occurs in chloride environments. A nominal relationship called PREN (Pitting Resistance Equivalent Number) has been developed and used for stainless steels. Table 1 shows S32101 in comparison to 304L and 316L. Critical Pitting Temperature (CPT) per ASTM G150 is a method to determine at what temperature pitting begins, which is shown in table 2. Based on this data, S32101 has pitting resistance at least equivalent to 316L. Critical Crevice Temperature (CCT) is common to evaluate crevice corrosion resistance using ASTM G48F. Alloys with higher CCT values are considered to be more resistance to crevice attack. Table 3 shows S32101 in comparison to 316L. Based on this data, S32101 has pitting and crevice corrosion resistance equal to or better than 304L and 316L. Where S32101 has an advantage over 304L and 316L is against Stress Corrosion Cracking (SCC). Much data has shown that S32101 is far superior against SCC than 304 SS. See Tables 4, 5, 6 & 7. Since 316L normally is only equal or slightly better than 304 against SCC, it can be assumed that S32101 will outperform 316L SS in SCC resistance.

Table 1[1]
PREN = Cr% + 3.3Mo% + 30N%

Alloy	PREN
LDX 2101®(S32101)	28
316L (S31603)	26
304L (S30403)	21

Table 2[1]
CPT 5.8%NaCl, ASTM G150

Alloy	CPT(°F)
LDX 2101®(S32101)	62
316L (S31603)	62
304L (S30403)	42

Table 3[2]
CCT 6%$FeCl_3$+1%NaCl, ASTM G48F

Alloy	CCT(°F)
LDX 2101®(S32101)	<32
316L (S31603)	<32

Table 4 SCC Results Measured in 4M $MgCl_2$ at 100°C {212°F} for 500 Hours[3]

Alloy	4-Point Load	U-Bend
LDX 2101®(S32101)	No SCC	No SCC
304L (S30403)	SCC and pitting	SCC

Table 5 U-bend test {40% $CaCl_2$ at 100°C}[1]

Alloy	4-Point Load
LDX 2101®(S32101)	No SCC after 500 hours
304L (S30403)	SCC Cracking at 75-100 hrs.

Table 6 Wick Test SCC Results using modified ASTM C692 Test NaCl (1500ppm) at 100°C {212°F} for 672 Hours[4]

Alloy	Qty tested	SCC failures
LDX 2101®(S32101)	6	0
304 (S30400)	2	2

Table 7 Chloride Deposits Test SCC 50°C {122°F}[4]

	Test Media-	$MgCl_2$		$CaCl_2$	
Alloy	Exposure (weeks)	Qty. Tested	SCC failures	Qty. Tested	SCC failures
LDX 2101®(S32101)	4	1	0	1	0
LDX 2101®(S32101)	22	2	0	2	0
304 (S30400)	4	1	1	1	1
304 (S30400)	22	2	2	2	2

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Testing was performed by DCI, Inc. to address pitting and crevice corrosion in an actual dimple jacket application. The test was performed on dimple jacket plug welded coupons (see Figure 2A). The coupons were tested using a 5% Ferric Chloride + 1% Sodium Nitrate test solution for 72 hours at 40^0C.[5,6]

Several samples were tested and in all samples there was significant weight loss due to pitting corrosion, however all the corrosion was on the 316L side whether it was the vessel back-up plate or the dimple jacket. Figure 2C shows a 316L vessel back-up plate with 316L dimple jacket. Pitting occurred on both 316L sides. Figure 2D shows LDX 2101® (S32101) dimple jacket welded to a 316L vessel back-up plate. Here, the weight loss occurred only on the 316L back-up plate (Figure 2B). No pitting was observed on the S32101 dimple jacket material. In all cases, no weld attack was observed.

Results from this test conclude that LDX 2101® (S32101) has pitting and crevice corrosion properties that are equal to and better than 304 and 316L in a dimple jacket application.

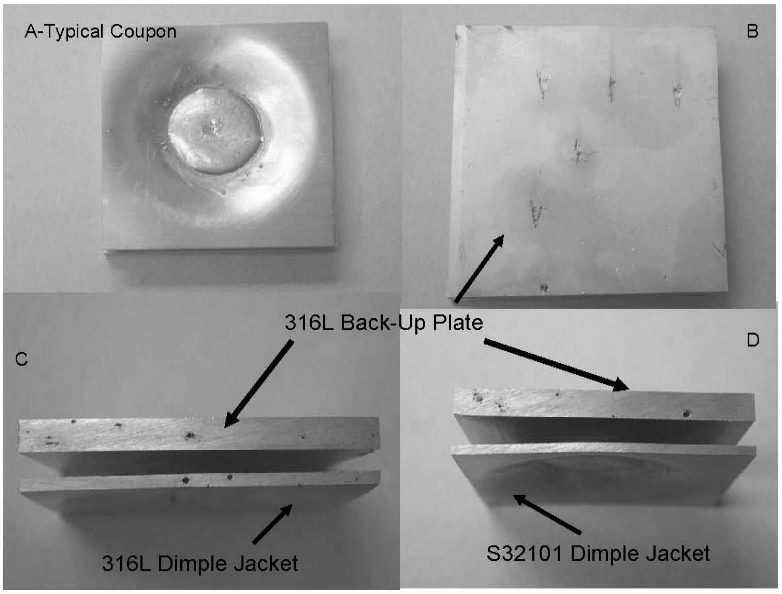

Figure 2-Corrosion Testing of Dimple Jacket Coupons

IV. Thermal Shocking of Dimple Jackets

The most common incorrect use of dimple jackets and most misunderstood is thermal shocking of dimple jackets. (Reference DCI technical document # X-7141.) Rapid temperature changes cause an unequal rate of thermal expansion between the thicker vessel wall and the thin dimple jacket material resulting in high thermal stresses and strains. If it is not addressed in the process, such as tempering, then it must be addressed by design and material selection to prolong the life of the vessel and dimple jacket. LDX 2101® (S32101) was investigated since it has mechanical and physical properties very similar to alloy 625 (N06625), which has had success in solving thermal shocking failures. The similar properties are lower thermal coefficient of expansion rate, higher strain at yield point (see table 8), and higher strength (see table 9).

Table 8 Comparison of Alloy Strain

Alloy	Thermal Conductivity (BTU*in/ft^2*hr*F)	Thermal Expansion Coefficient (@70F) (in/F)*	0.2% Yield Strength, YS (ksi) }	Modulus of Elasticity, E (@200F) (ksi)	Strain, at Yield Point** (in/in) %	Strain used in LCF testing (proportional to 316L value)
316/316L (SA-240)	114	9.0×10^{-6}	30	27.5×10^6	0.00109	0.00494
S32101 (SA-240)	143	7.4×10^{-6}	77	28.2×10^6	0.00273	0.00407
N06625 (SB-443, Gr1)	68	7.2×10^{-6}	60	29.4×10^6	0.00204	0.00396

*Obtained from producer's data sheets ** Calculated from yield strength/elastic modulus

Table 9 ASME Section VIII, Division 1, Allowable Design Values (ksi){MPa} (ASME Section II)
(note: dual certified values for SA-240,316/316LSS, values of S32101 for t<0.25" {6.5mm} per Code Case 2418)[7,8]

Alloy	Design Stress 100^0F{40^0C}	Design Stress 200^0F{90^0C}	Design Stress 300^0F{150^0C}	Design Stress 400^0F{200^0C}	0.2% Yield Strength	Ultimate Tensile Strength
316/316L (A/SA-240)	20.0 {138}	20.0 {138}	20.0 {138}	19.3 {134}	30 {205}	75 {575}
S32101 (SA-240)	28.9 {200}	28.9 {200}	27.5 {190}	26.5 {184}	77 {530}	101 {700}
N06625 (SB-443, Gr1)	34.3 {216}	34.3 {216}	34.3 {215}	33.6 {213}	60 {380}	120 760}

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To determine if LDX 2101® (S32101) was a viable thermal shock resistance material for dimple jacket use, it was tested in an experiment to address Low-Cycle Fatigue (LCF) caused by thermal shocking. The LCF testing parameters were to first find a strain level of 316L for failure in the LCF regime. This data was tested at a higher strain value than normally seen in a DJ application due to stress risers, and should be considered conservative. Then S32101 and N06625 strain levels were chosen in direct proportion to the coefficient of thermal expansion of each alloy. 16ga test strips were used, strained from zero to the predetermined tensile strain at a frequency of 0.5Hz. The results are found in Table 10.

Table 10 LCF Testing Results[5,9]

Alloy	Sample Description (roll direction)	Strain	Cycles	Observations
316L	Parallel to applied strain	0.493	15,894	Low Cycle Fatigue Failure
316L	Parallel to applied strain	0.493	41,663	Low Cycle Fatigue Failure
316L	Parallel to applied strain	0.487	43,200	Test Discontinued
316L	Parallel to applied strain	0.494	43,200	Test Discontinued
S32101	Parallel to applied strain	0.405	534,462	Test Discontinued
S32101	Parallel to applied strain	0.404	43,200	Test Discontinued
S32101	Transverse to applied strain	0.402	43,200	Test Discontinued
S32101	Transverse to applied strain	0.403	43,200	Test Discontinued
S32101	Parallel to applied strain-GTAW butt welded	0.404	43,200	Test Discontinued
S32101	Parallel to applied strain-same strain applied as S31603	0.494	43,200	Test Discontinued
S32101	Parallel to applied strain-same strain applied as S31603	0.491	25,457	Low Cycle Fatigue Failure
N06625	Parallel to applied strain	0.395	43,200	Test Discontinued
N06625	Parallel to applied strain	0.394	42,753	Test Discontinued

Conclusions from the LCF testing were that for 316L at an applied strain of ~0.494, 50% failed in the LCF regime and S32101 samples strained at ~0.494 strain had 50% failures. However, when the S32101 was tested at a proportional strain (by coefficient of thermal expansion) of ~0.405, 0% failed in LCF regime and one sample tested past 40,000 cycles, actually achieved over 500,000 cycles and still did not fail. The S32101 LCF properties were not reduced in transverse direction or in the as welded condition. Therefore, if the same temperature is applied to a vessel in a thermal shock application, the results suggest that S32101 dimple jackets will provide better resistance to repetitive thermal stresses or thermal shock than 316L. N06625 was not tested to failure and presumed equivalent or better than S32101, therefore it has not been determined if S32101 will perform to the level of N06625 in a thermal shock application.

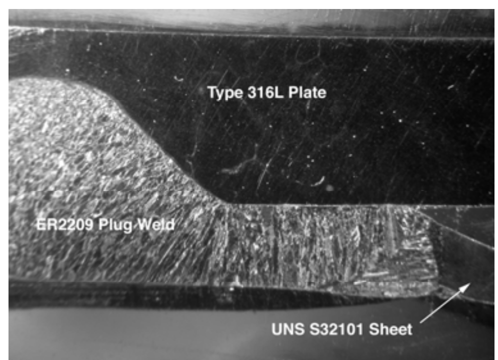

Figure 3-Macrosection of Plug Weld

V. High Cycle Fatigue

Table 11 Fatigue, Pulsating Tensile Test (R=0.1), room temp[1,2]

Alloy-	316L	LDX 2101® (S32101)
0.2% Yield Strength (ksi)	40	69
Ultimate Tensile Strength (ksi)	83	100
Fatigue Strength (ksi)	52	72

VI. Weld Properties & Microstructures

Duplex stainless steel microstructures are dual phase, meaning they contain approximately 50% austenite and 50% ferrite, compared to a fully austenitic metallurgy like typical stainless 304, 316L and nickel alloys (see Figures 5 & 6). The key with the duplex alloys is to keep the structure as balanced as possible after welding. In addition, you must avoid creating any sigma phase or intermetallics that could lose strength, toughness, and corrosion resistance. Although a lean duplex, like S32101, is less likely to have these problems, one must perform microstructures during weld procedure qualifications and check ferrite levels after welding for verification.

Dimple Jacket Plug Welds per ASME Section VIII, Division 1, Appendix 17, 17-1(b)(3) were analyzed and the following was shown:

- Good weld penetration and no defects were found (see Figure 3)
- Desirable austenite/ferrite ratio in weld and HAZ can be achieved
    - Nitrogen addition in welding gas keeps ferrite level lower and in a more desirable range (see Table 12)
    - Microstructures showed no deficiencies (see Figure 4)
    - Sigma phase and intermetallic formation is unlikely in this type of plug welded application using filler wire

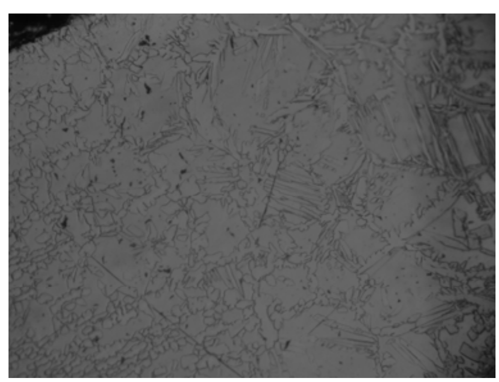

Figure 4-Typical Microstructure of HAZ & Plug Weld using 69% Argon/30% Helium/1% Nitrogen Weld Gas

DCI's standard dimple jacket design where the dimple jacket is preformed and punched and plug welds are made using the GMAW process were investigated. It was found with using ER2209 filler wire and nitrogen gas additions, acceptable microstructures and acceptable ferrite levels between 25-70% were consistently obtained.

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From the data collected, DCI recommends using weld gas with 1% nitrogen addition for plug welding. Dimple jacket manufacturing using autogenous welding (without filler wire) such as Resistance Welding, Laser Welding, etc., (without post weld heat treatment), and "inflated" after welding were not tested. Superior weld properties are achieved when ER2209 Duplex Filler Wire is used when welding onto 304, 304L, 316/316L, and duplex alloys. LDX 2101® (S32101)'s high thermal conductivity and lower coefficient of thermal expansion promotes lower thermal stresses during welding than austenitic stainless steels[10] and is advantages to avoid hot cracking and will result in lower residual stresses associated with welds as well.

Table 12 Ferrite Percentage Measurements in S32101 Duplex Plug Weld Samples on 316L Back-Up Plate (average of 10 readings minimum)[5]

Area	DJ Sample # 2	DJ Sample # 3	DJ Sample # 7
Filler Wire of Plug Weld	ER316L	ER2209	ER2209
Weld Gas	75He/25Ar	75Ar/25He	69Ar/30He/1N
S32101 Base DJ Material	40%	40%	40%
HAZ	32%	37%	36%
Plug Weld	14%	65%	56%

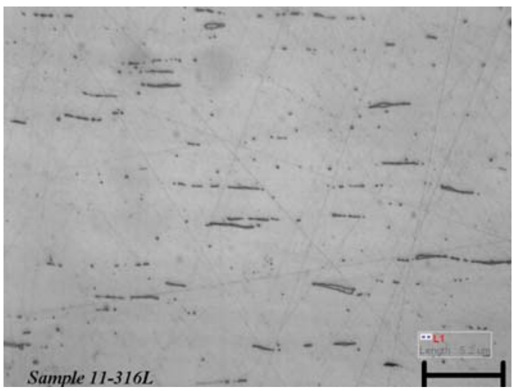

Figure 5-Typical 316L Austenitic Microstructure (with delta ferrite stringers present)

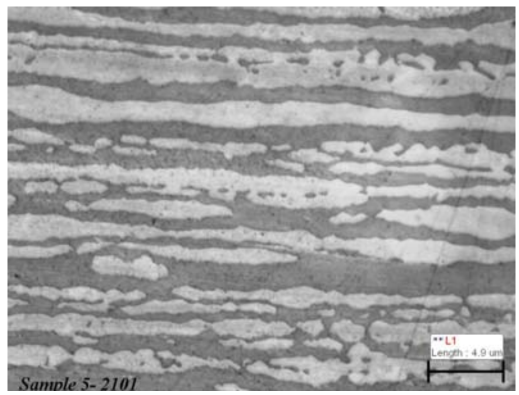

Figure 6-Typical S32101 Duplex Microstructure

VI. Alloy Chemistry

Table 16 shows the chemistry comparison of the alloys discussed in this data sheet. Duplex LDX 2101® has higher chrome than 304 and 316L and lower nickel, with the addition of a controlled amount of nitrogen, which is very typical of all duplex alloys to maintain the microstructure. Duplex LDX 2101® also has a specific amount of molybdenum and manganese. The amount of molybdenum helps with the pitting resistance and manganese makes up for the smaller amount of nickel. As can be seen, Duplex LDX 2101® has a low nickel and low molybdenum content, allowing the cost to be more stable as the commodity market changes and allows it to be very competitive with 304 and 316L.

Table 13 Alloy Chemistry Chart[11,12,13]

Alloy (UNS#)	C (max.)	Cr	Ni	Mo	Fe	N	Mn	Other
304/304L (S30400/30403)	0.08/0.030	18.0-20.0	8.0-10.5/12.0	-	Balance	0.10 max.	2.00 max.	P,S,Si
316/316L (S31600/31603)	0.08/0.030	16.0-18.0	10.0-14.0	2.00-3.00	Balance	0.10 max.	2.00 max.	P,S,Si
Duplex LDX 2101® (S32101)	0.040	21.0-22.0	1.35-1.70	0.10-0.80	Balance	0.20-0.25	4.0-6.0	P,S,Si,Cu
Duplex 2205 (S31803/S32205)	0.030	22.0-23.0	4.5-6.5	3.0-3.5	Balance	0.14-0.20	2.00 max.	P,S,Si
Inconel® 600 (N06600)	0.15	14.0-17.0	72.0 min.	-	6.0-10.0	-	1.0 max.	S,Si,Cu
Inconel® 625 (N06625)	0.10	20.0-23.0	58.0 min.	8.00-10.00	5.0 max.	-	0.50 max.	P,S,Si,Cu,Al,Nb,Ti,Co

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Other helpful related DCI Technical Data Sheets:
X-7141 Thermal Shocking of Dimple Jackets
X-7258 Heat Transfer Surface Designs

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Duplex LDX 2101® Stainless Steel for dimple jackets is another one of those solutions!

Contact DCI today (sales@dciinc.com) and let our Sales and Engineering Professionals assist with your specific heat transfer applications.

Helpful information to assist with your application is: tank volume, tank area available, desired temperature, heat transfer media, available media temperature, tank/product temperature, product data (viscosity, specific gravity, specific heat), time requirement, thermal shock/non-thermal shock, heat/cool/hold requirements.

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