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SmartWeld Working Session for the GTS4

Stephen Kleban, Ken Hicken, Ray Ng, Bernie Fricke

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Stephen Kleban
Sandia National Laboratories
Albuquerque, NM 87185

Ken Hicken and Ray Ng
Sandia National Laboratories
Livermore, CA 94551

Bernie Fricke
Allied Signal Kansas City Division
Kansas City, Missouri

Abstract

Results from SmartWeld's first working session involving in-progress designs is presented. The Welding Advisor component of SmartWeld was thoroughly exercised, evaluating all eleven welds of the selected part. The Welding Advisor is an expert system implemented with object-oriented techniques for knowledge representation . With two welding engineers in attendance, the recommendations of the Welding Advisor were thoroughly examined and critiqued for accuracy and for areas of improvement throughout the working session. The Weld Schedule Database component of SmartWeld was also exercised. It is a historical archive of proven, successful weld schedules that can be intelligently searched using the current context of SmartWeld's problem solving state. On all eleven welds, the experts agreed that Welding Advisor recommended the most risk free options. As a result of the Advisor's recommendation, six welds agreed completely with the experts, two welds had their joint geometry modified for production, and three welds were not modified but extra care was exercised during welding.

Acknowledgements

We wish to acknowledge the efforts of K.W. Mahin, without whose vision the SmartWeld system would never have happened. We also acknowledge John Mitchiner for the successful management of such a large and diverse project. Barry Hess, Dave Missink, and Gregroy Gershanok are also acknowledged for their great efforts and talents in producing a successful software system. Finally, we appreciate the support for the working session from Ed Cull.

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Nomenclature

GTS4	Gas Transfer System 4
GTAW	Gas Tungsten Arc Weld
PAW	Plasma Arc Weld
Nd:YAG	Neodymium:Yttrium Aluminum Garnet laser weld
GMAW	Gas Metal Arc Weld
CSD	Cut, Seal, and Divert
AS/KCD	Allied Signal / Kansas City Division
WA	Weld Advisor
WSDB	Weld Schedule Data Base
TMS	Tool Made Sample

Introduction

On July 16, 1996, SNL and AS/KCP personnel met in Livermore, CA to evaluate SmartWeld as it evaluated the then current GTS4 weld designs. SmartWeld is a sophisticated weld design and analysis system. It consists of a ten step procedure to get from part definition to the visualization of the thermal analysis. Product designers can use the system to get initial information about acceptable weld joint designs. Welding engineers can use the Welding Advisor (WA) to more completely and more systematically explore welding options and search the Weld Schedule Database (WSDB) for weld schedules that have proven successful in the past. This working session involved only the first three steps of 1) defining the part, 2) using the Welding Advisor, and 3) obtaining the weld schedule from the WSDB.

The goal of this session was to use real parts and real designs to assess the utility of these tools for product designers and weld engineers. During this five hour session, the attendees, Kleban, Hicken, Ng, and Fricke, exercised these SmartWeld components on the eleven weld joint configurations planned for the GTS4. The current set of engineering drawings and specific chemical compositions of the materials planned for this part were used in this activity. This paper will present the analysis of each of the eleven welds.

SmartWeld's First Three Steps

The top level SmartWeld window is shown in Figure 1. The series of steps to perform thermal analysis are "behind" the "Finite Element Analysis" button. This working session focused exclusively on the first three buttons in the center of the window. By clicking on "Define Part" another window appears to enter part and weld information as shown in Figure 2. Here, the user selects the piece part configuration as depicted on icons and identifies the part by giving it a part name. Figure 2 shows a hemisphere-to-plate weld. Every possible joint configuration is not depicted by icons, so a best fit decision must be made. Each piece part is parameterized depending on its shape, with thickness being of primary concern to the weld advisor. Also, the function of the weld must be defined as either structural, hermetic, or attachment. A structural weld is one whose primary function is to bear substantial levels of mechanical stress. They are generally required to be full penetration. Hermetic welds are primarily used to prevent access of fluids, gases or liquids, from one region to another, and attachment welds join two parts together without the requirement to be structural or hermetic.

Once the part and weld are defined, the user clicks on "Done" at the bottom of the "Define Part" window and is returned to the top level SmartWeld window where the next step, the "Weld Advisor" is invoked. At this time, the WA begins analyzing the weld, querying the user for more detailed information as necessary as shown in Figure 3. Each question has a "Help" button associated with it for further clarification. After the weld is fully described, a table of results is presented as shown in Figure 4. Each row is a weld scenario, consisting of a process and joint geometry. The scenarios are ordered by their score (see Score column) which is a sum of how well it performed on each of the tests (see columns to the right of Score). For further explanation of the scenario performance, the user may select a scenario and click on "Explanation" at the bottom of the table and another window will appear with the details as shown in Figure 5.

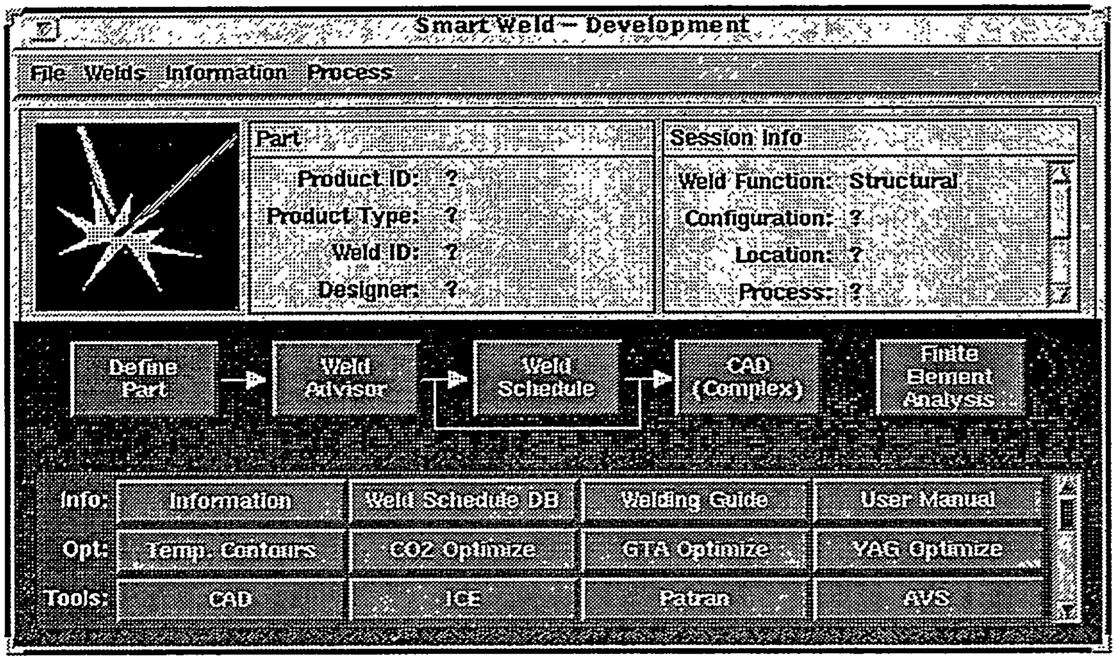


Figure 1. Top level SmartWeld window. The "Finite Element Analysis" button is for detailed thermal analysis.

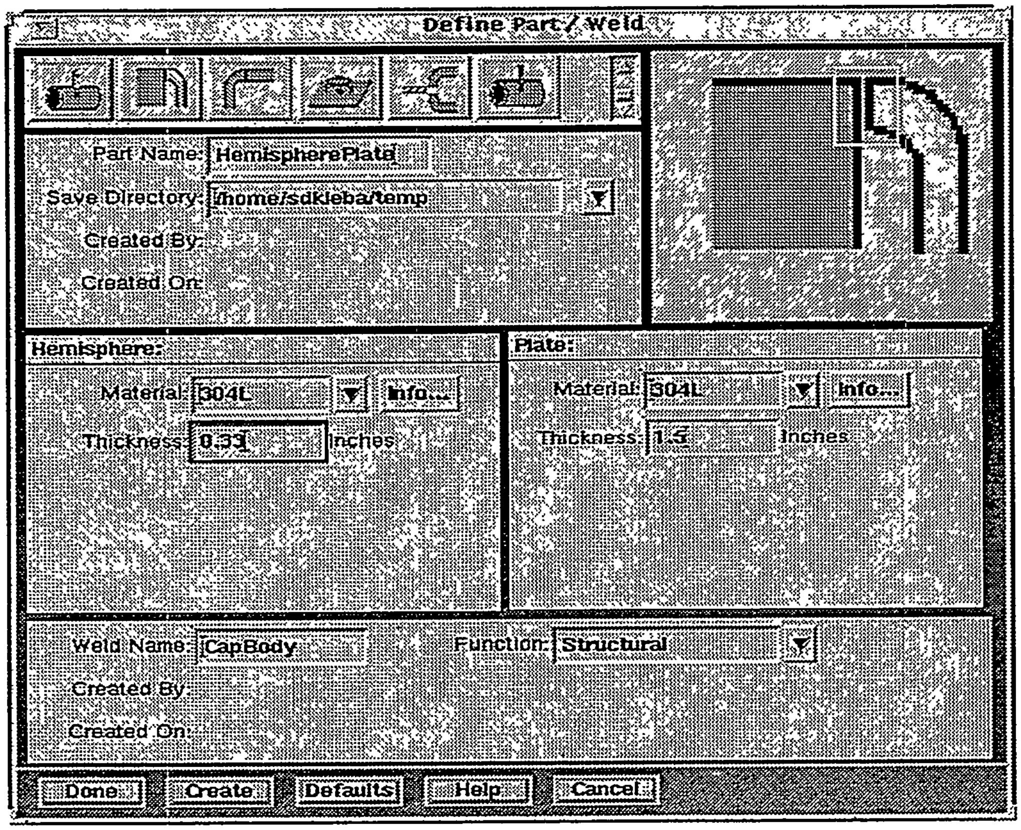


Figure 2. This window obtains the part and weld information from the user.

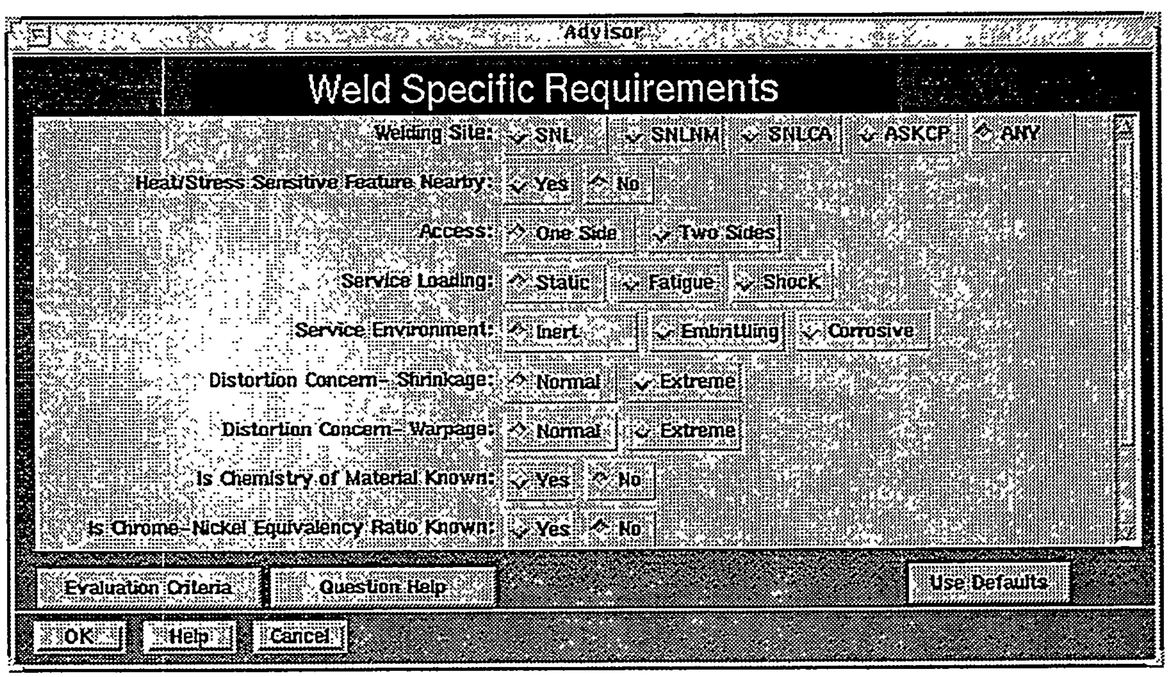
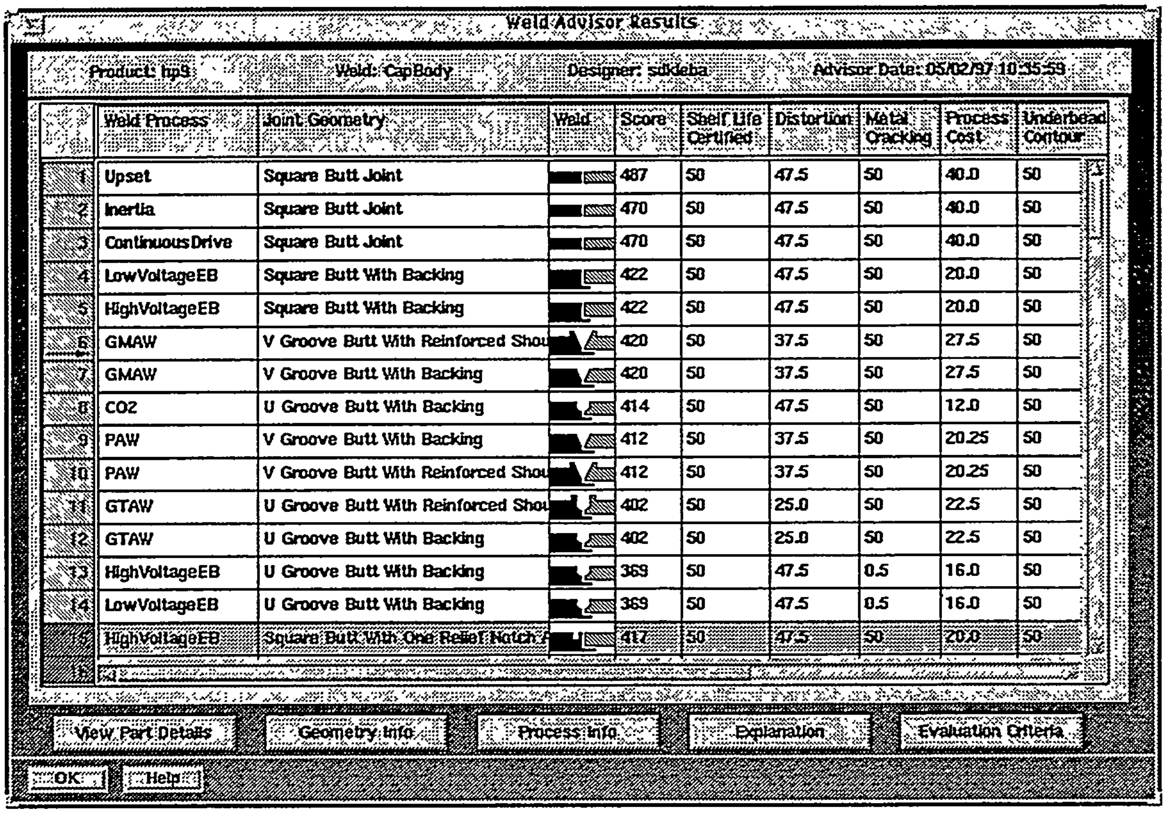


Figure 3. The Weld Advisor queries the user for more specific weld requirements.



	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour
1	Upset	Square Butt Joint		487	50	47.5	50	40.0	50
2	Inertia	Square Butt Joint		470	50	47.5	50	40.0	50
3	ContinuousDrive	Square Butt Joint		470	50	47.5	50	40.0	50
4	LowVoltageEB	Square Butt With Backing		422	50	47.5	50	20.0	50
5	HighVoltageEB	Square Butt With Backing		422	50	47.5	50	20.0	50
6	GMAW	V Groove Butt With Reinforced Shou		420	50	37.5	50	27.5	50
7	GMAW	V Groove Butt With Backing		420	50	37.5	50	27.5	50
8	CO2	U Groove Butt With Backing		414	50	47.5	50	12.0	50
9	PAW	V Groove Butt With Backing		412	50	37.5	50	20.25	50
10	PAW	V Groove Butt With Reinforced Shou		412	50	37.5	50	20.25	50
11	GTAW	U Groove Butt With Reinforced Shou		402	50	25.0	50	22.5	50
12	GTAW	U Groove Butt With Backing		402	50	25.0	50	22.5	50
13	HighVoltageEB	U Groove Butt With Backing		369	50	47.5	0.5	16.0	50
14	LowVoltageEB	U Groove Butt With Backing		369	50	47.5	0.5	16.0	50
15	HighVoltageEB	Square Butt With One Relief Notch A		417	50	47.5	50	20.0	50
16									

Figure 4. The table of results as output by the Weld Advisor.

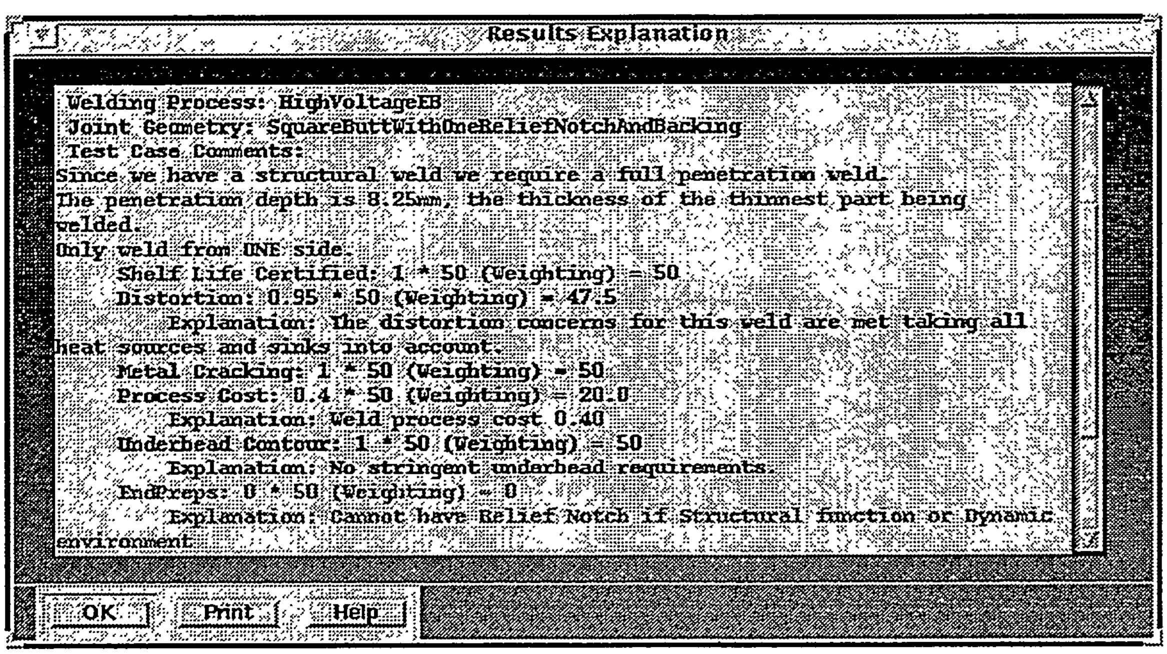


Figure 5. The detailed explanation of weld number 15 in Figure 4. It failed the "EndPreps" test because relief notches are not allowed with a structural weld function.

The Eleven Welds for GTS4

The GTS4 is a three chambered work bottle consisting of eleven welds attaching caps, tubes, stems, plungers, and disk to bodies. The structural components (caps and bodies) are made from 304L stainless steel forgings. The forgings have been worked to produce a yield strength between 65,000 and 80,000 psi. The other components are made from bar, tubing and sheet. The chemistries for all metals used in GTS4 are shown in Table 1 along with who provided the analysis and the component's name. (Anamet is an independent service company which performs chemical analysis)

Table 1. GTS4 Material Chemistries

Source	Component	C	Cr	Cu	Mn	Mo	Ni	P	Si	S	Ti	N
Vender	CSD Tube	.021	18.36	.24	1.07	.02	8.29	.028	.44	.003		
Anamet	CSD Tube	.034	18.32	.24	1.13	.02	8.4	.013	.40	.005		
Vender	Stem Plug	.023	18.15	.18	1.55	.23	8.13	.023	.44	.026		.080
Anamet	Stem Plug	.017	18.53	.0	1.55	.21	7.95	.016	.43	.025		
Vender	CSD Plngr	.020	18.49	.43	1.14	.29	8.78	.028	.38	.002	.01	.034
Anamet	CSD Plnge	.019	18.88	.37	1.03	.27	8.82	.020	.36	.001		
Vender	Fill Stem	.016	16.49	.35	1.84	2.22	12.82	.027	.31	.026		.097
Anamet	Fill Stem	.009	16.57	.32	1.79	2.24	12.7	.026	.33	.022		
Vender	CapA BodyA	.021	19.7		1.69	.079	11.5	.013	.49	.0021	.05	.038
Vender	CapB	.021	19.2		1.7	.025	10.3	.013	.48	.0015		.028
Vender	BodyB	.021	18.7		1.7	.085	10.7	.017	.70	.003	.063	.036
Vender	Disc	.025	18.07	.34	1.66	.08	9.0	.031	.52	.004		.08
Anamet	Disc	.028	18.42	.43	1.7	.041	8.92	.027	.50	.006	.005	

Weld 1 and 2: "CSD Tube" to "Body A"

The "CSD Tube" to "Body A" weld is a tube welded through a solid body (Figure 1.) The "CSD Tube" is welded on both ends to "Body A" (welds 1 and 2). The joint is a butt or corner weld attaching a tube to a solid. Our joint design model assumes tubes are protruding and one side access is from the outside, these assumptions would be incorrect in this case. Therefore, the joint was described to SmartWeld as a corner weld configuration with a hermetic seal weld function. In SmartWeld, a corner weld consists of a housing and a plate. The "CSD Tube" is approximated by the housing with a wall thickness of .023" and "Body A" is approximated by the plate with a .500" thickness (Figure 6). The tube is the darker piece part in Figure 6 and is weld at each end. Both piece parts are made of 304L stainless steel.

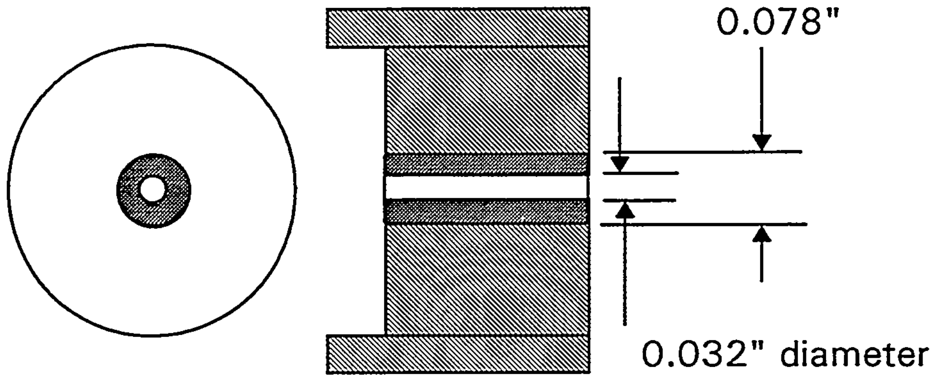


Figure 6. Joint design for "CSD Tube" to "Body A".

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any		
b) Heat/Stress Sensitive feature Nearby:	No		
c) Access:	One Side		
d) Service Environment:	Embrittling		
e) Distortion Concern - Shrinkage:	Normal		
f) Distortion Concern - Warpage:	Normal		
g) Material Chemistry - CSD Tube:	Cr/Ni Equiv. Ratio	=	2.04
	Ferrite Number	=	13.795
	Weldability	=	Excellent
- Body A:	Cr/Ni Equiv. Ratio	=	1.51
	Ferrite Number	=	1.71
	Weldability	=	Medium

The Cr/Ni equivalency ratio calculations are due to the work performed by John Brooks Dept. 8240, SNL. They are applicable to austenitic stainless steels (300 Series) where the Weld Advisor's rating system is presented in Table 2. The Advisor either considers a Cr/Ni value for a material either weldable or not (yes/no) for each of the arc, beam, and laser fusion processes.

Table 2. Weld Advisor's weldability rating system.

Cr/Ni	Weld Advisor Rating	GTAW/PAW	Electron Beam	Laser
< 1.5	Poor	no	no	no
1.5 - 1.6	Medium	yes	no	no
1.6 - 1.7	Good	yes	yes	no
> 1.7	Excellent	yes	yes	yes

Situations where the Advisor considers a material not weldable can be improved if filler metal additions are practical. The GMAW weld process has filler metal additions as part of the process so its weldability is always good. The Ferrite number is also an important indicator for fusion processes. Generally, if the Ferrite number is above 3 or 4, the stainless steel is considered weldable by the Arc processes (GTAW, PAW). Ferrite number is also important in beam welding processes (electron, laser) and a ferrite number of 4 to 8 is desirable. The rapid solidification possible with the beam process can result in hot crack-susceptible austenite being retained in the weld metal. The user interface window for entry of the material chemistry and display of the weldability parameters is shown in Figure 7.

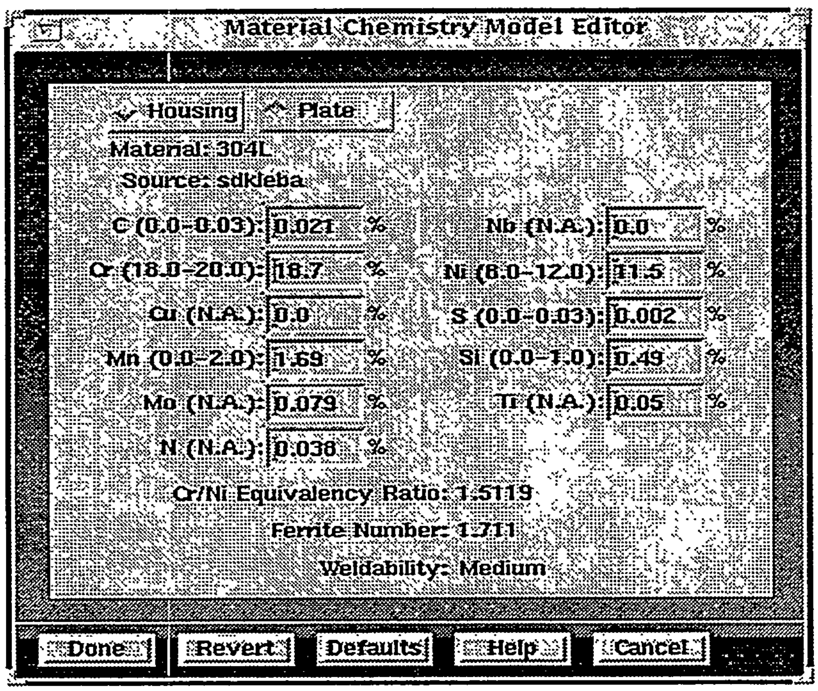


Figure 7. The SmartWeld material chemistry editor. The specific material chemistry is entered for each material used in the weld and the weldability performance parameters are calculated.

The table of results as output by the Weld Advisor is shown in Figure 8.

Weld Advisor Results

Product: CSDTubeBodyA   Weld: Lid   Designer: [illegible]   Advisor Date: 02/25/97 14:57:59

	Weld Process	Joint Geometry	Weld	Score	Metal Cracking	Process Cost	Underbead Contour	Distortion	EndPreps
1	HighVoltageEB	Corner With Relief Notches		392	50	20.0	50	47.5	25.0
2	LowVoltageEB	Corner With Relief Notches		392	50	20.0	50	47.5	25.0
3	CO2	Corner With Relief Notches		387	50	15.0	50	47.5	25.0
4	Nd:YAG	Corner With Relief Notches		385	50	10.0	50	50.0	25.0
5	PAW	Corner With Relief Notches		385	50	22.5	50	37.5	25.0
6	GTAW	Corner With Relief Notches		375	50	25.0	50	25.0	25.0
7	HighVoltageEB	Corner With Relief Notches And Align		367	50	20.0	50	47.5	Failed
8	LowVoltageEB	Corner With Relief Notches And Align		367	50	20.0	50	47.5	Failed
9	GMAW	Corner With Relief Notches And Align		365	50	27.5	50	37.5	Failed
10	CO2	Corner With Relief Notches And Align		362	50	15.0	50	47.5	Failed
11	PAW	Corner With Relief Notches And Align		360	50	22.5	50	37.5	Failed
12	Nd:YAG	Corner With Relief Notches And Align		360	50	10.0	50	50.0	Failed
13	GTAW	Corner With Relief Notches And Align		350	50	25.0	50	25.0	Failed
14	HighVoltageEB	Corner Joint		342	Failed	20.0	50	47.5	25.0
15	LowVoltageEB	Corner Joint		342	Failed	20.0	50	47.5	25.0

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

OK | Help

Figure 8. Weld Advisor table of results for "CSD Tube" to "Body A" weld.

Again, this edge weld is approximated by a corner weld and this is reflected in the joint picture in Figure 8. Because the weldability of the metal used for the body is considered adequate only for Arc processes, the Electron Beam and Laser processes scenarios have a recommended relief notch to alleviate stress and potential cracking. Although the Arc processes do not require relief notches for potential cracking problems, the notches are still recommended (in scenarios 5 and 6 in Figure 8) for heat flow balance between two significantly different piece part thicknesses, .020" and .500". This detailed information is obtained by selecting a scenario and clicking "Explanation" at the bottom of the table.

Analysis

The planned weld for this joint was a partial penetration square butt joint performed by the Nd:YAG Laser process. Since the discovery of the poor weldability of "Body A", the welding engineers agreed with the Welding Advisor to include a relief notch to reduce the stress at the joint and thereby alleviate the cracking concerns. Additionally, Laser beam welds were scheduled to be made in the actual forged material to confirm a crack free weld could be produced. The relief notch as shown in Figure 9 is now part of the design. There were no schedules in the WSDB that were similar to this weld in terms of material, penetration depth, and weld process.

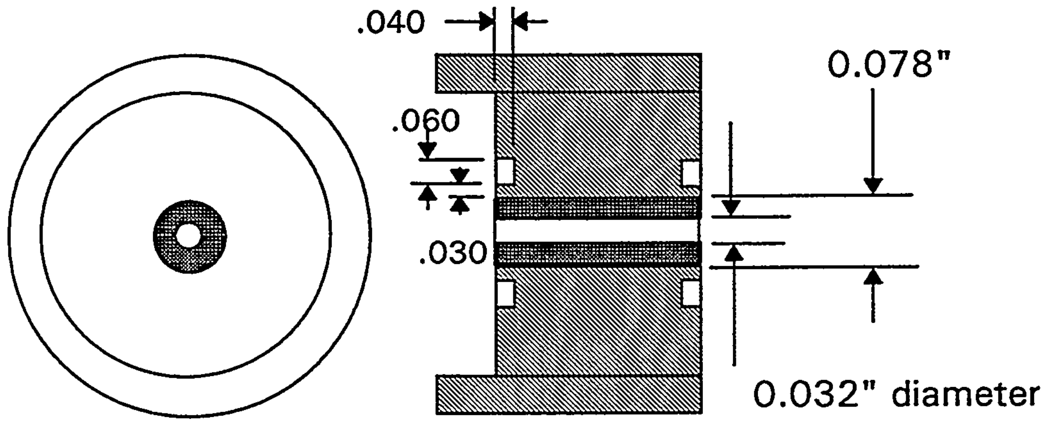


Figure 9. "CSD Tube" to "Body A" modified with relief notches

Weld 3: "Stem Plug" to "Body B" Internal

To analyze a plug weld in SmartWeld, one chooses the plug in a cylinder weld configuration in "Define Part." The "Stem Plug" is defined to be .060" thick and the thickness of "Body B" is .500" (see Figure 10). The weld function is defined as attachment. Both piece parts are 304L stainless steel.

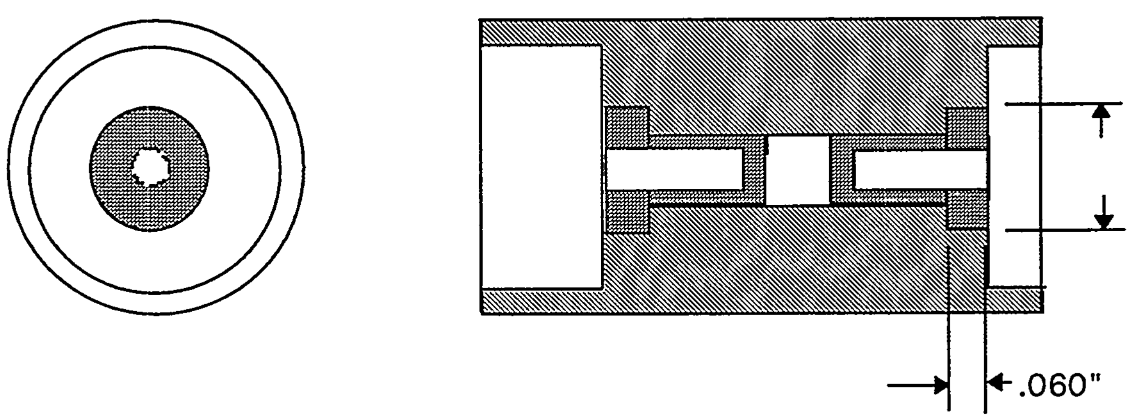


Figure 10. "Stem Plug" to "Body B" weld configuration . Left internal, right external.

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any
b) Heat/Stress Sensitive feature Nearby:	No
c) Access:	One Side

d) Service Environment: Inert
e) Distortion Concern - Shrinkage: Normal
f) Distortion Concern - Warpage: Normal
g) Material Chemistry - Stem Plug: Cr/Ni Equiv. Ratio = 1.83
Ferrite Number = 6.17
Weldability = Excellent
- Body B: Cr/Ni Equiv. Ratio = 1.64
Ferrite Number = 5.56
Weldability = Good
h) Is there Line of Sight to the Weld: Yes
i) Is there room for a Laser Nozzle: No
j) Is there room for an Arc Torch: No
k) Certified Shelf Life Required: No

The table of results as output by the Weld Advisor is shown in Figure 11. From answering the Laser Nozzle and Arc Torch access questions in the negative, those processes were subsequently eliminated by the advisor. Only line of sight to weld is required by the Electron Beam processes.

Weld Advisor Results

Product: StemPlugBodyB Weld: Plug Designer: sdkeba Advisor Date: 02/26/97 15:21:23

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Polar Access	Metal Cracking	Process Cost	Underbead Contour
1	Upset	PlugAttachment		512	50	50	50	40.0	50
2	Upset	PlugCountersunk		512	50	50	50	40.0	50
3	LowVoltageEB	PlugFlushReliefNotch		472	50	50	50	20.0	50
4	HighVoltageEB	PlugFlushReliefNotch		472	50	50	50	20.0	50
5	HighVoltageEB	PlugFlush		447	50	50	5.0	20.0	50
6	LowVoltageEB	PlugFlush		447	50	50	5.0	20.0	50
7	Upset	PlugAttachmentReliefNotch		442	50	50	Failed	40.0	50
8	Upset	PlugCountersunkReliefNotch		442	50	50	Failed	40.0	50
9	CO2	PlugFlushReliefNotch		417	50	Failed	50	15.0	50
10	Nd:YAG	PlugFlushReliefNotch		415	50	Failed	50	10.0	50
11	PAW	PlugFlushReliefNotch		415	50	Failed	50	22.5	50
12	GTAW	PlugFlushReliefNotch		405	50	Failed	50	25.0	50
13	PAW	PlugFlush		390	50	Failed	5.0	22.5	50
14	CO2	PlugFlush		387	50	Failed	Failed	15.0	50
15	Nd:YAG	PlugFlush		385	50	Failed	Failed	10.0	50
16									

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

OK | Help

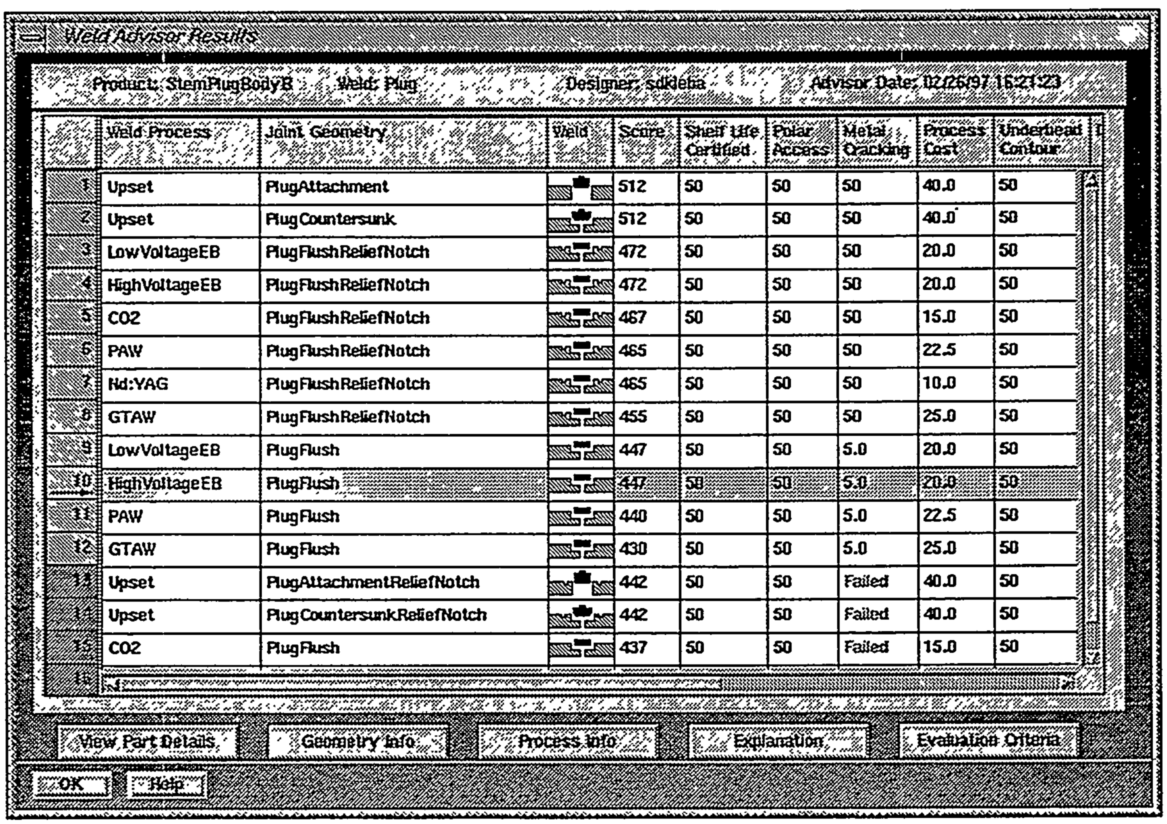
Figure 11. Weld Advisor output for “Stem Plug” to “Body B” Internal weld.

Analysis

The welding engineers agreed with the WA recommendations. All the recommended processes and joints would have yielded excellent results. The Upset welding process was not chosen because of the possibility of the reduced diameter of the stem making contact other than at the interface. The relief notches were not necessary because of the weldable chemistries of the two components. We chose the High Voltage Electron Beam welding process because of ease of tooling and process experience. Also, note that welds 3 and 4 have a relief notch and would seem to score lower than welds 5 and 6 without the relief notch because of the cost of machining the joint. However, the advisor likes the relief notch to balance heat flow because of the significant difference in piece part thicknesses. Again, no similar weld schedules were found in the WSDB. In fact, when this working session took place, only about twenty weld schedules were in the WSDB and none of them were very similar to the welds on the GTS4.

Weld 4: "Stem Plug" to "Body B" External

This weld is exactly the same as Weld 3 except that it is "External" which means there is plenty of room for a Laser nozzle or an Arc torch. When we answer the Laser and Arc access questions in the affirmative, the table of results is as shown in Figure 12.


Weld Advisor Results

Product: StemPlugBodyB Weld: Plug Designer: sdkleba Advisor Date: 02/26/97 16:21:23

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Polar Access	Metal Cracking	Process Cost	Underbead Contour
1	Upset	PlugAttachment		512	50	50	50	40.0	50
2	Upset	PlugCountersunk		512	50	50	50	40.0	50
3	LowVoltageEB	PlugFlushReliefNotch		472	50	50	50	20.0	50
4	HighVoltageEB	PlugFlushReliefNotch		472	50	50	50	20.0	50
5	CO2	PlugFlushReliefNotch		467	50	50	50	15.0	50
6	PAW	PlugFlushReliefNotch		465	50	50	50	22.5	50
7	Nd:YAG	PlugFlushReliefNotch		465	50	50	50	10.0	50
8	GTAW	PlugFlushReliefNotch		455	50	50	50	25.0	50
9	LowVoltageEB	PlugFlush		447	50	50	5.0	20.0	50
10	HighVoltageEB	PlugFlush		447	50	50	5.0	20.0	50
11	PAW	PlugFlush		440	50	50	5.0	22.5	50
12	GTAW	PlugFlush		430	50	50	5.0	25.0	50
13	Upset	PlugAttachmentReliefNotch		442	50	50	Failed	40.0	50
14	Upset	PlugCountersunkReliefNotch		442	50	50	Failed	40.0	50
15	CO2	PlugFlush		437	50	50	Failed	15.0	50

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

OK | Help

Figure 12. Weld Advisor table of results for "Stem Plug" to "Body B" External weld.

Analysis

All the processes and joints recommended by the WA would work on these materials. The welding engineer choose to use the Nd:YAG for this weld because of equipment load levels.

Weld 5: "Fill Stem A" to "Body A"

This is a stem/tube to body Attachment weld. "Fill Stem A" has a shoulder that is .104" thick. This gets welded into a .130" deep counterbore in "Body A" which is .500" thick as shown in Figure 13. The stem is made of 316 stainless steel and the body is 304L.

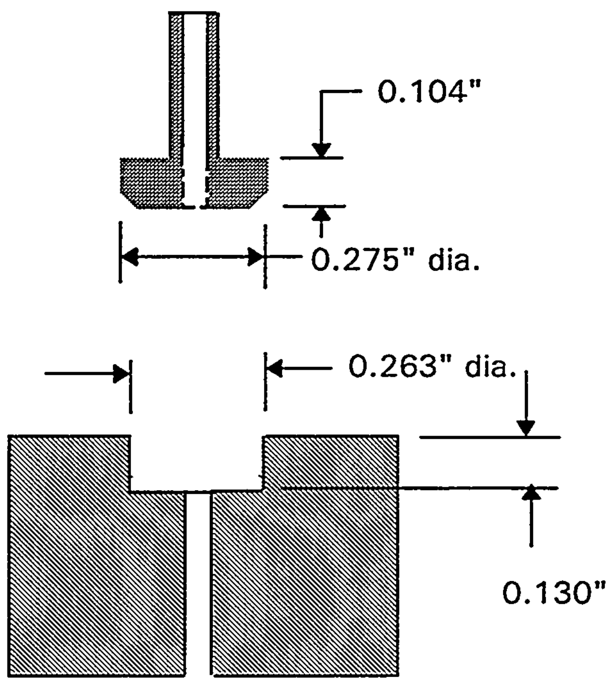


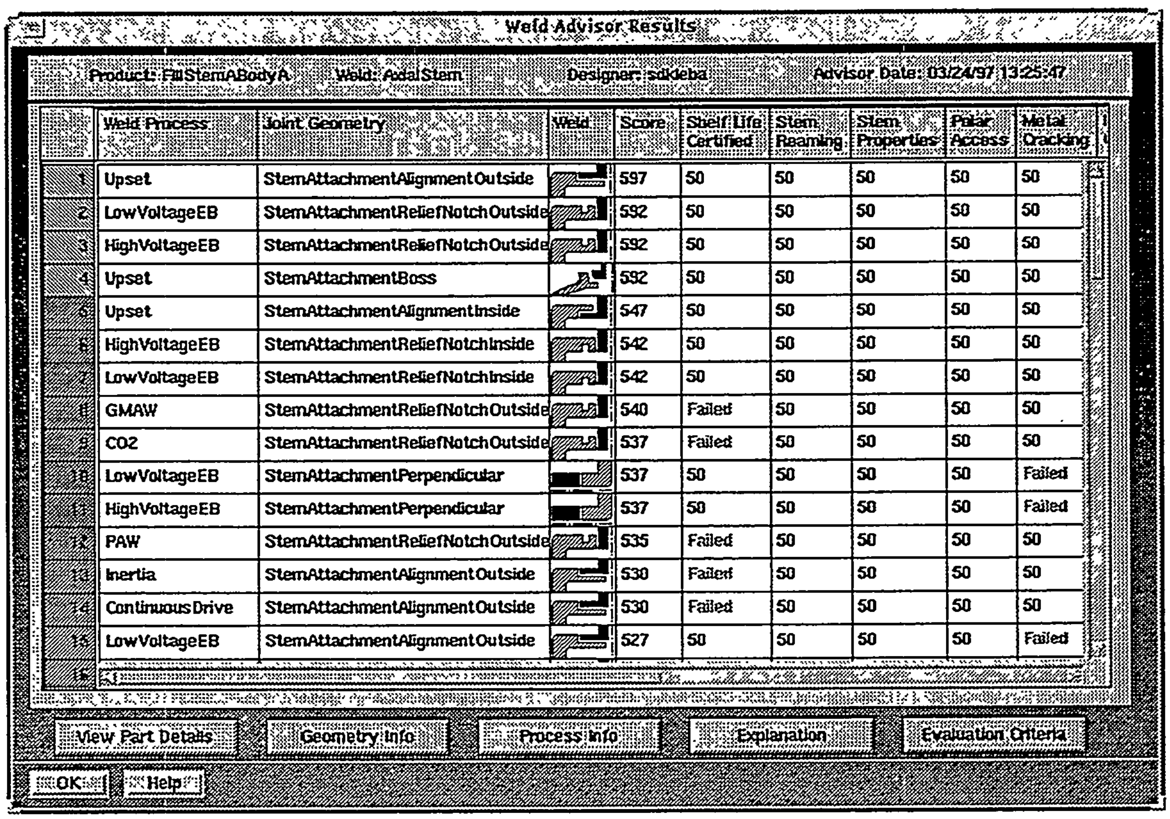
Figure 13. "Fill Stem A" to "Body A" weld configuration.

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any
b) Heat/Stress Sensitive feature Nearby:	No
c) Access:	One Side
d) Service Environment:	Embrittling
e) Distortion Concern - Shrinkage:	Normal

f)	Distortion Concern - Warpage:	Normal	
g)	Material Chemistry - Fill Stem A:	Cr/Ni Equiv. Ratio	= 1.29
		Ferrite Number	= -8.69
		Weldability	= Poor
	- Body A:	Cr/Ni Equiv. Ratio	= 1.51
		Ferrite Number	= 1.71
		Weldability	= Medium
h)	Is there Line of Sight to the Weld:	Yes	
i)	Is there room for a Laser Nozzle:	Yes	
j)	Does Stem have a Fitting:	No	
k)	Does Stem need O-ring Seal:	No	
l)	Full Bore Stem Diameter Required:	No	
m)	Certified Shelf Life Required:	Yes	

The table of results as output by the Weld Advisor is shown in Figure 14.



Weld Advisor Results

Product: FillStemABodyA   Weld: AxialStem   Designer: sdkleba   Advisor Date: 03/24/97 13:25:47

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Stem Reaming	Stem Properties	Polar Access	Metal Cracking
1	Upset	StemAttachmentAlignmentOutside		597	50	50	50	50	50
2	LowVoltageEB	StemAttachmentReliefNotchOutside		592	50	50	50	50	50
3	HighVoltageEB	StemAttachmentReliefNotchOutside		592	50	50	50	50	50
4	Upset	StemAttachmentBoss		592	50	50	50	50	50
5	Upset	StemAttachmentAlignmentInside		547	50	50	50	50	50
6	HighVoltageEB	StemAttachmentReliefNotchInside		542	50	50	50	50	50
7	LowVoltageEB	StemAttachmentReliefNotchInside		542	50	50	50	50	50
8	GMAW	StemAttachmentReliefNotchOutside		540	Failed	50	50	50	50
9	CO2	StemAttachmentReliefNotchOutside		537	Failed	50	50	50	50
10	LowVoltageEB	StemAttachmentPerpendicular		537	50	50	50	50	Failed
11	HighVoltageEB	StemAttachmentPerpendicular		537	50	50	50	50	Failed
12	PAW	StemAttachmentReliefNotchOutside		535	Failed	50	50	50	50
13	Inertia	StemAttachmentAlignmentOutside		530	Failed	50	50	50	50
14	ContinuousDrive	StemAttachmentAlignmentOutside		530	Failed	50	50	50	50
15	LowVoltageEB	StemAttachmentAlignmentOutside		527	50	50	50	50	Failed

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

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Figure 14. "Fill Stem A" to "Body A" table of results from the Welding Advisor.

Analysis

The advisor listed the Upset welding process as the first choice. This choice was made because the Upset weld is a Solid State weld and the materials are not intended to melt, therefore, the poor *fusion* weldability rating for the materials will have no affect on the Upset weld. The two Electron Beam welds options 2 and 3, would result in a fillet weld which is less crack sensitive than a butt joint. The resistance Upset side bond weld recommended by the advisor was used. This process is widely accepted in the DOE complex and Sandia has used it extensively. Fixturing is often available.

Weld 6: "Fill Stem B" to "Body B"

"Fill Stem B" is made from the same material as "Fill Stem A", but "Body B" has a more weldable chemistry (see Table 1). Again, the advisor recommends resistance Upset welding which will be used.

Weld 7: "Plunger Disk" to "Body B"

This weld is modeled in SmartWeld as a disk to a plate. Both piece parts are made of 304L stainless steel. The "Plunger Disk" has a thickness of .010" and "Body B" has a thickness of .500". The weld function is Hermetic. The actual geometry is shown in Figure 15.

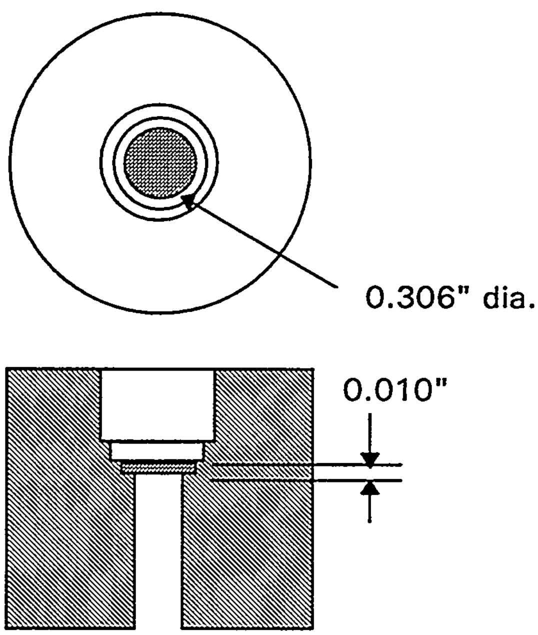


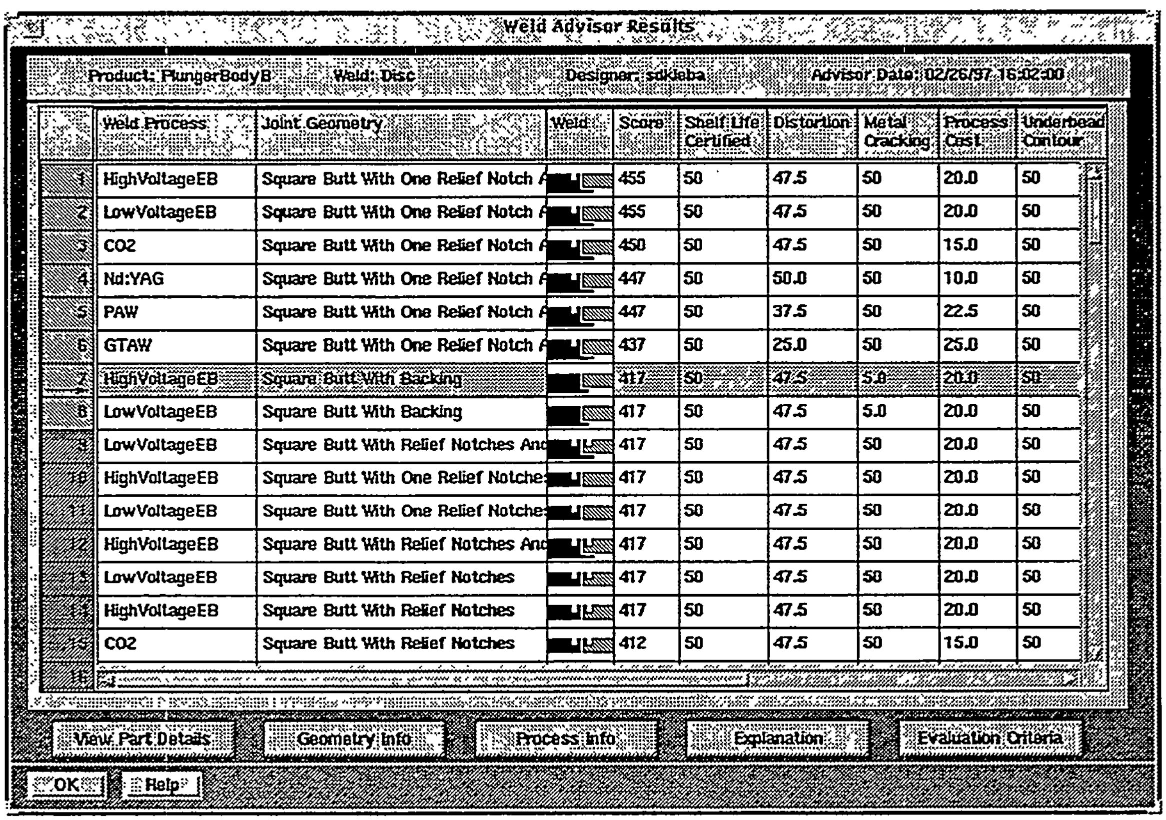
Figure 15. The "Plunger Disk" to "Body B" weld.

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any		
b) Heat/Stress Sensitive feature Nearby:	No		
c) Access:	One Side		
d) Service Environment:	Inert		
e) Distortion Concern - Shrinkage:	Normal		
f) Distortion Concern - Warpage:	Normal		
g) Material Chemistry - Plunger Disk:	Cr/Ni Equiv. Ratio	=	1.64
	Ferrite Number	=	2.78
	Weldability	=	Good
- Body B:	Cr/Ni Equiv. Ratio	=	1.64
	Ferrite Number	=	5.56
	Weldability	=	Good
h) Certified Shelf Life Required:	No		

Note that the Cr/Ni equivalency ratio is the same for the two materials but the ferrite numbers are different. This is because they are derived from two different equations.

The table of results from the Welding Advisor is shown in Figure 16.



	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour
1	HighVoltageEB	Square Butt With One Relief Notch A		455	50	47.5	50	20.0	50
2	LowVoltageEB	Square Butt With One Relief Notch A		455	50	47.5	50	20.0	50
3	CO2	Square Butt With One Relief Notch A		450	50	47.5	50	15.0	50
4	Nd:YAG	Square Butt With One Relief Notch A		447	50	50.0	50	10.0	50
5	PAW	Square Butt With One Relief Notch A		447	50	37.5	50	22.5	50
6	GTAW	Square Butt With One Relief Notch A		437	50	25.0	50	25.0	50
7	HighVoltageEB	Square Butt With Backing		417	50	47.5	5.0	20.0	50
8	LowVoltageEB	Square Butt With Backing		417	50	47.5	5.0	20.0	50
9	LowVoltageEB	Square Butt With Relief Notches And		417	50	47.5	50	20.0	50
10	HighVoltageEB	Square Butt With One Relief Notches		417	50	47.5	50	20.0	50
11	LowVoltageEB	Square Butt With One Relief Notches		417	50	47.5	50	20.0	50
12	HighVoltageEB	Square Butt With Relief Notches And		417	50	47.5	50	20.0	50
13	LowVoltageEB	Square Butt With Relief Notches		417	50	47.5	50	20.0	50
14	HighVoltageEB	Square Butt With Relief Notches		417	50	47.5	50	20.0	50
15	CO2	Square Butt With Relief Notches		412	50	47.5	50	15.0	50

Figure 16. "Plunger Disk" to "Body B" results from the Welding Advisor.

Analysis

The actual weld we used was weld number 7, a High Voltage Electron Beam, Square Butt joint with backing. The reason welds 1 and 2 scored higher than 7 and 8 is that the advisor likes the relief notch to balance the heat flow and reduce cracking when the two piece parts have a significant piece part thickness difference as described in the explanation window for weld 7 in Figure 17. The WA did account for the higher cost of joint preparations that include a relief notch by scoring the "Endpreps" test (not visible in Figure 16 because the column is to the right in the table and is off screen) where the end prep with the relief notch scored a 5 (weld 1 and 2) and without a relief notch, scored 25 (weld 7 and 8). Even so, the Laser beam welds rated above the Electron Beam and would have been a good choice for this weld. Allied Signal expressed a preference for Electron Beam which fit within Allied's and Sandia's experience base. The Arc processes would not work in this instance because the disc is recessed below the surface.

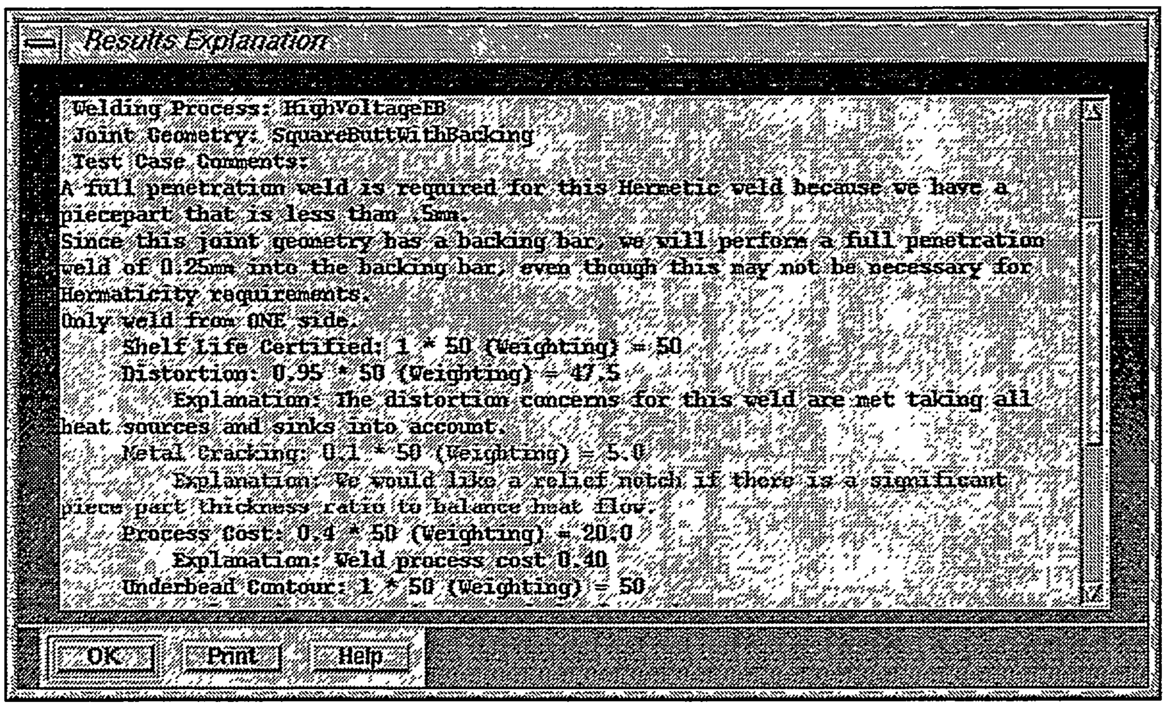


Figure 17. Explanation for weld number 7, a High Voltage Electron Beam, Square Butt joint with backing (no relief notch).

At this point the design engineer can feel comfortable with his design knowing that several processes and joints could be used successfully for this weld. The welding engineer now makes decisions on which recommendation to follow based on equipment schedules and experience at his facility.

Weld 8: "CSD Plunger" to "Body A"

The "CSD Plunger" to "Body A" is described to SmartWeld as a disk to plate weld. The details are shown in Figure 18. The disk has thickness .010" and the body thickness is .500". Both parts are made of 304L stainless steel. The weld function is Hermetic.

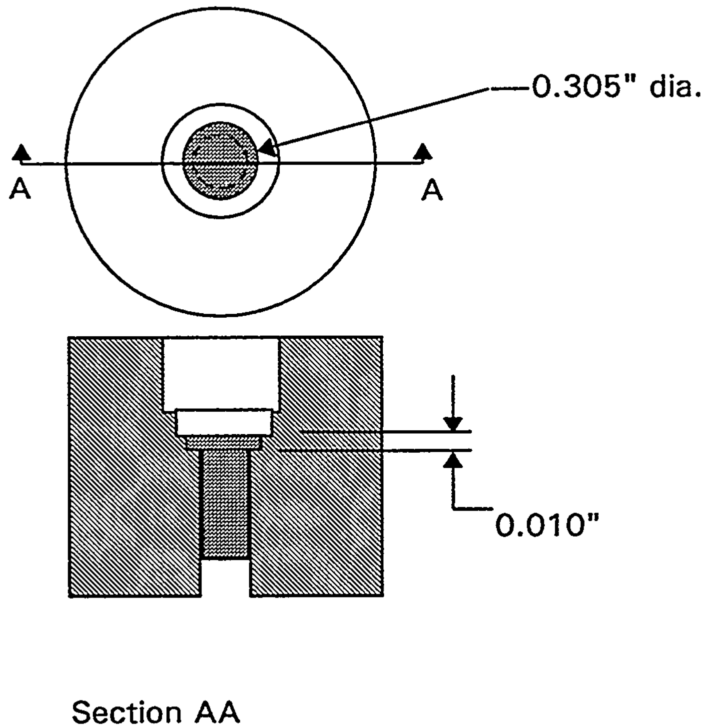


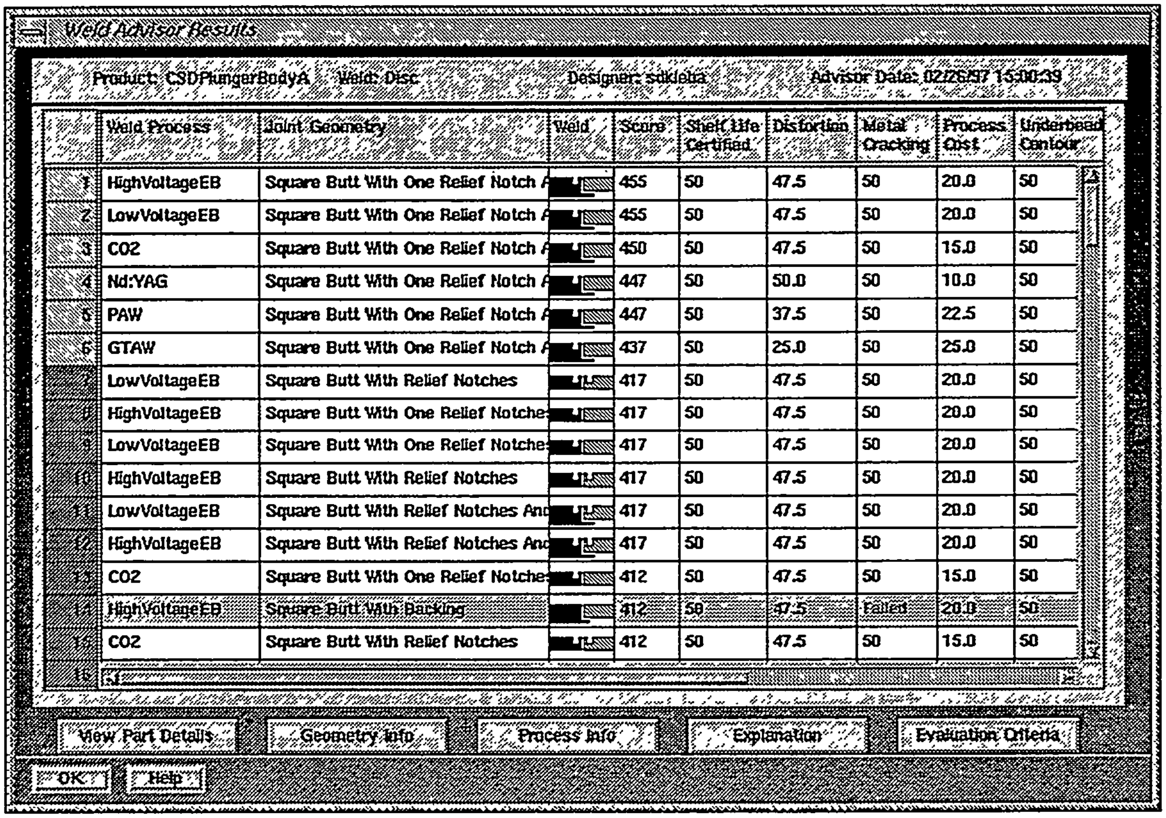
Figure 18. "CSD Plunger" to "Body A" weld.

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any		
b) Heat/Stress Sensitive feature Nearby:	No		
c) Access:	One Side		
d) Service Environment:	Inert		
e) Distortion Concern - Shrinkage:	Normal		
f) Distortion Concern - Warpage:	Normal		
g) Material Chemistry - CSD Plunger:	Cr/Ni Equiv. Ratio	=	1.85
	Ferrite Number	=	10.49
	Weldability	=	Excellent
- Body A:	Cr/Ni Equiv. Ratio	=	1.51

	Ferrite Number	= 1.71
	Weldability	= Medium
h) Certified Shelf Life Required:	No	

The table of results from the Welding Advisor is shown in Figure 19.



Weld Advisor Results

Product: CSDPlungerBodyA Weld: Disc Designer: sdkleba Advisor Date: 02/26/97 15:00:39

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour
1	HighVoltageEB	Square Butt With One Relief Notch A		455	50	47.5	50	20.0	50
2	LowVoltageEB	Square Butt With One Relief Notch A		455	50	47.5	50	20.0	50
3	CO2	Square Butt With One Relief Notch A		450	50	47.5	50	15.0	50
4	Nd:YAG	Square Butt With One Relief Notch A		447	50	50.0	50	10.0	50
5	PAW	Square Butt With One Relief Notch A		447	50	37.5	50	22.5	50
6	GTAW	Square Butt With One Relief Notch A		437	50	25.0	50	25.0	50
7	LowVoltageEB	Square Butt With Relief Notches		417	50	47.5	50	20.0	50
8	HighVoltageEB	Square Butt With One Relief Notche		417	50	47.5	50	20.0	50
9	LowVoltageEB	Square Butt With One Relief Notche		417	50	47.5	50	20.0	50
10	HighVoltageEB	Square Butt With Relief Notches		417	50	47.5	50	20.0	50
11	LowVoltageEB	Square Butt With Relief Notches An		417	50	47.5	50	20.0	50
12	HighVoltageEB	Square Butt With Relief Notches An		417	50	47.5	50	20.0	50
13	CO2	Square Butt With One Relief Notche		412	50	47.5	50	15.0	50
14	HighVoltageEB	Square Butt With Backing		412	50	47.5	Failed	20.0	50
15	CO2	Square Butt With Relief Notches		412	50	47.5	50	15.0	50
16									

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

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Figure 19. The results from the Welding Advisor for the "CSD Plunger Disk" to "Body A" weld.

Analysis

The Welding Advisor recommended a relief notch to lessen the risk of cracking for the Electron Beam and Laser processes. For the Arc processes, it recommended a relief notch to help balance the heat flow since the piece parts have significantly different thicknesses. The welding engineers excluded the Arc processes because the depth of the recess precludes Arc processes because of the size of the welding torches. The WA's recommendation for relief notches is correct. We chose to use the Electron Beam process with a butt joint with backing (weld 14) even though the "Body A" material has poor weldability for beam processes. This choice was based on additional information not addressed within the advisor. The weld size (width) is restricted because of a seal that is required at the inside edge of the weld. The Electron Beam process has been demonstrated to meet the size requirement on other programs. Also, the physical geometry eliminates the possibility of a machined relief notch. Notice that the first and only joint geometry in the table of results that does not have a relief notch is Weld 14, (the High Voltage Electron Beam, square butt joint with backing) the one that was used.

Weld 9: "Cap A" to "Body A"

The "Cap A" to "Body A" weld is modeled in SmartWeld as a Hemisphere to Cylinder weld. The cap has a thickness of .190" and the cylinder was .115". A drawing of the configuration is shown in Figure 20. Both piece parts are made of 304L stainless steel. The function of this weld is Structural.

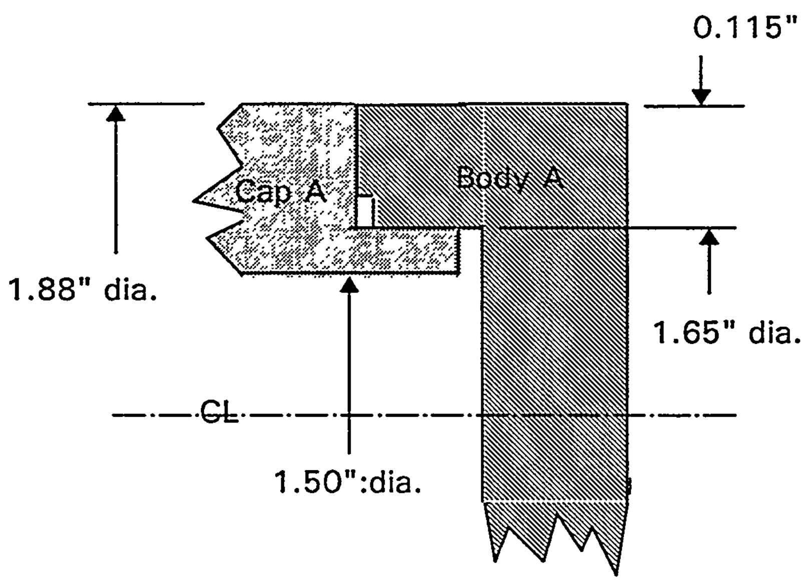


Figure 20. The "Cap A" to "Body A" weld.

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any
b) Heat/Stress Sensitive feature Nearby:	No
c) Access:	One Side
d) Service Environment:	Embrittling
e) Service Loading:	Static
f) Distortion Concern - Shrinkage:	Normal

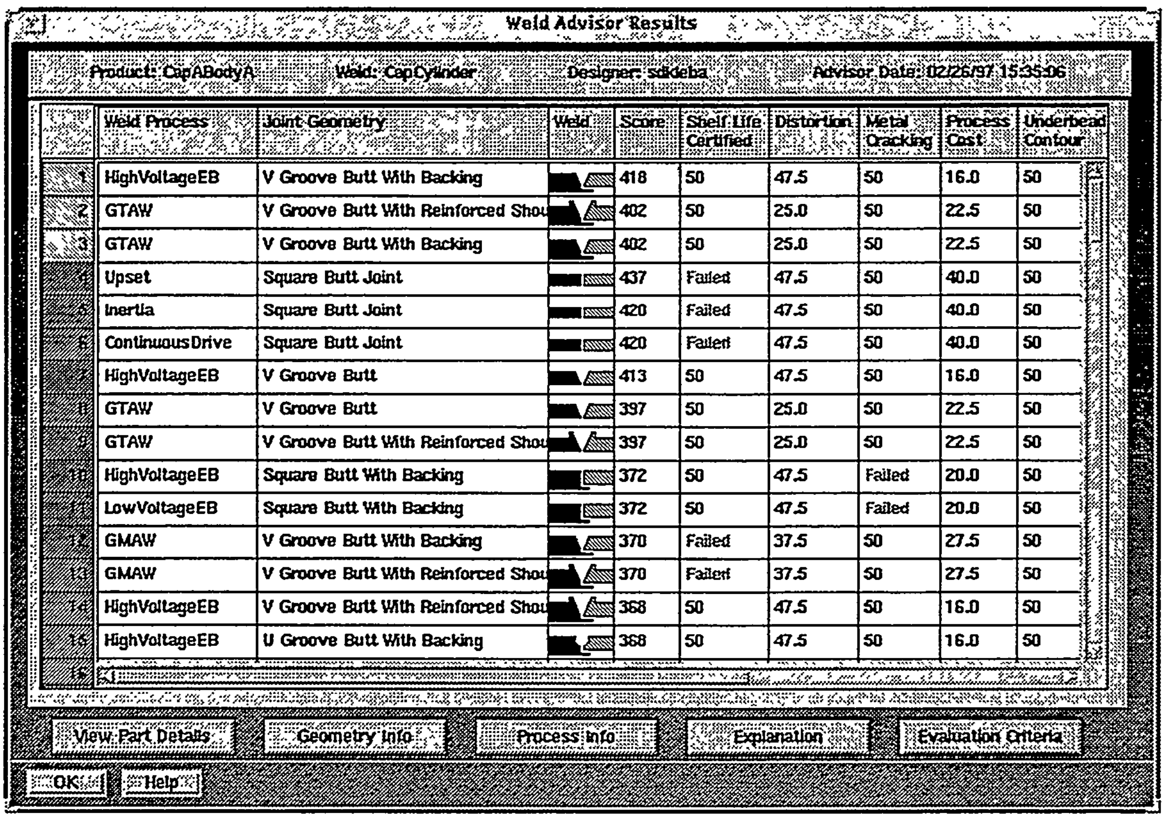
g) Distortion Concern - Warpage: Normal

h) Material Chemistry - Cap A: Cr/Ni Equiv. Ratio = 1.51
Ferrite Number = 1.71
Weldability = Medium

- Body A: Cr/Ni Equiv. Ratio = 1.51
Ferrite Number = 1.71
Weldability = Medium

h) Certified Shelf Life Required: Yes

The table of results from the Welding Advisor is shown in Figure 21.



Weld Advisor Results

Product: CapABodyA Weld: CapCylinder Designer: sdkeba Advisor Date: 02/26/97 15:35:06

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour
1	HighVoltageEB	V Groove Butt With Backing		418	50	47.5	50	16.0	50
2	GTAW	V Groove Butt With Reinforced Shou		402	50	25.0	50	22.5	50
3	GTAW	V Groove Butt With Backing		402	50	25.0	50	22.5	50
4	Upset	Square Butt Joint		437	Failed	47.5	50	40.0	50
5	Inertia	Square Butt Joint		420	Failed	47.5	50	40.0	50
6	ContinuousDrive	Square Butt Joint		420	Failed	47.5	50	40.0	50
7	HighVoltageEB	V Groove Butt		413	50	47.5	50	16.0	50
8	GTAW	V Groove Butt		397	50	25.0	50	22.5	50
9	GTAW	V Groove Butt With Reinforced Shou		397	50	25.0	50	22.5	50
10	HighVoltageEB	Square Butt With Backing		372	50	47.5	Failed	20.0	50
11	LowVoltageEB	Square Butt With Backing		372	50	47.5	Failed	20.0	50
12	GMAW	V Groove Butt With Backing		370	Failed	37.5	50	27.5	50
13	GMAW	V Groove Butt With Reinforced Shou		370	Failed	37.5	50	27.5	50
14	HighVoltageEB	V Groove Butt With Reinforced Shou		368	50	47.5	50	16.0	50
15	HighVoltageEB	U Groove Butt With Backing		368	50	47.5	50	16.0	50

View Part Details | Geometry Info | Process Info | Explanation | Evaluation Criteria

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Figure 21. The results from the Welding Advisor for the "Cap A" to "Body A" weld.

Analysis

The Electron Beam and GTAW welds recommended by the welding advisor have a V groove for the addition of filler metal to improve the weldability of the "Body A" and "Cap A" material. In addition, the GTAW weld requires a grooved geometry to meet the full penetration requirements. A structural weld requires full penetration and in this case the weld would be .100", too thick for GTAW in low sulfur material. The reinforced shoulders would be used for a large production run to allow the use of simple heat sinks.

The V groove weld is recommended because the end prep costs are less and the advisor does not recommend U grooves for joints thinner than .120". Hicken would recommend the U groove GTAW with reinforced shoulders (because of well established weld schedules) with equal wall thicknesses for a large production run where the tooling costs could be amortized over many parts. The solid state weld scored favorably but they are not Shelf Life certified. This weld size is very similar to weld number 10, Body B to Cap B . A set of development experiments could be eliminated if the same process was used for both welds. We choose the Electron Beam, square butt with backing (no V groove, weld scenario 10 in Figure 21) because of the minimum weld tooling required, low heat input, and favorable production history. This is a joint not recommended by the Welding Advisor and care must be used to assure cracking does not occur.

Weld 10: "Cap B" to "Body B"

The "Cap B" to "Body B" weld is very similar to the "Cap A" to "Body A" weld except for slightly different thicknesses. "Cap B" is .205" thick and "Body B" is .105" thick. It is also modeled in SmartWeld as a hemisphere to cylinder weld. Both piece parts are made of 304L stainless steel. The details of this joint can be found in Figure 22. The function of this weld is Structural.

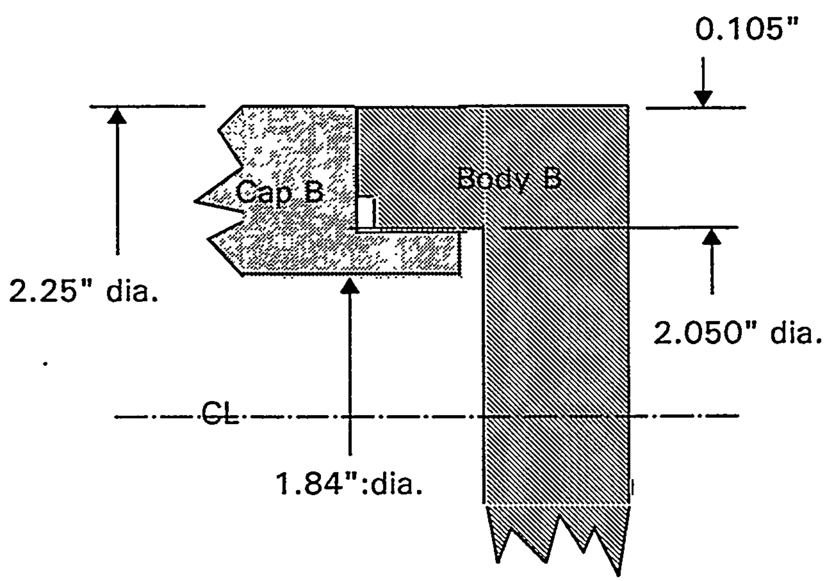


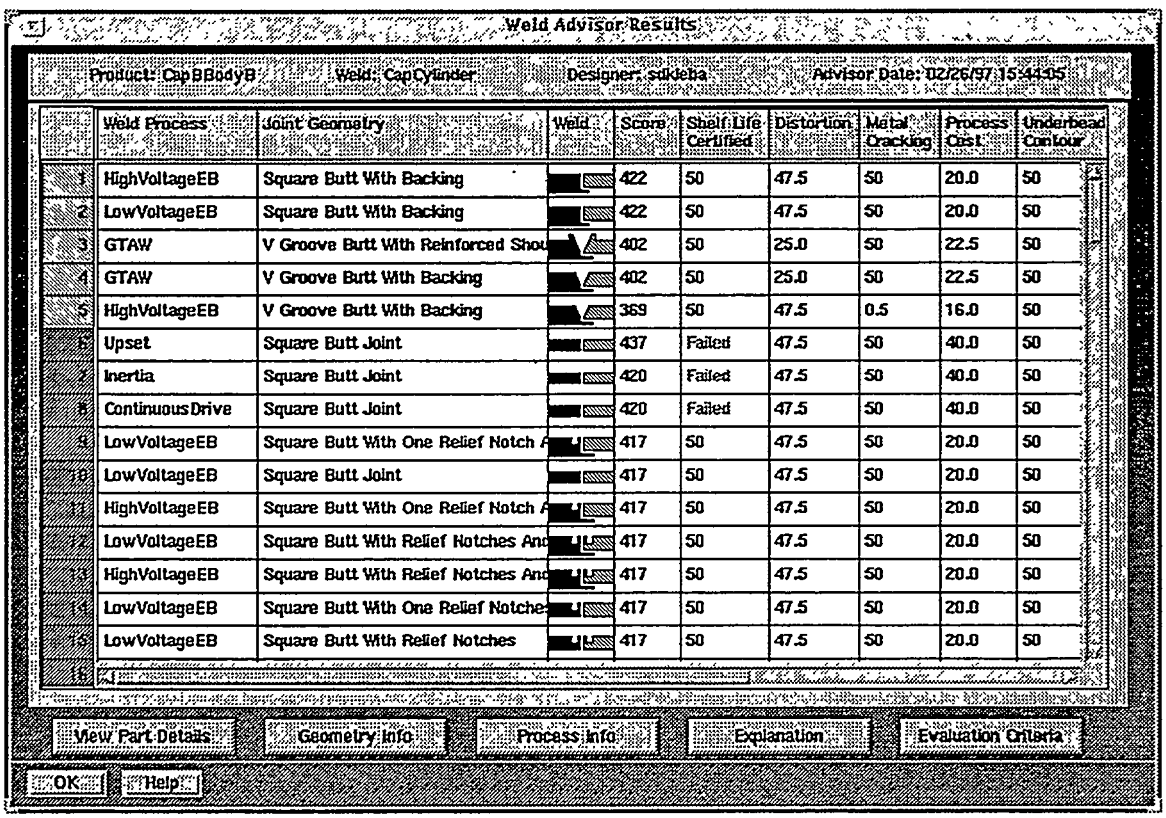
Figure 22. "Cap B" to "Body B" weld configuration.

The answers to the "Weld Specific Requirements" were:

a) Welding Site: Any
b) Heat/Stress Sensitive feature Nearby: No

c) Access: One Side
d) Service Environment: Embrittling
e) Service Loading: Static
f) Distortion Concern - Shrinkage: Normal
g) Distortion Concern - Warpage: Normal
h) Material Chemistry - Cap B: Cr/Ni Equiv. Ratio = 1.7
Ferrite Number = 7.92
Weldability = Excellent
- Body B: Cr/Ni Equiv. Ratio = 1.64
Ferrite Number = 5.56
Weldability = Good
h) Certified Shelf Life Required: Yes

The table of results from the Welding Advisor is shown in Figure 23.



Weld Advisor Results

Product: CapBBodyB Weld: CapCylinder Designer: sdkleba Advisor Date: 02/26/97 15:44:05

	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour
1	HighVoltageEB	Square Butt With Backing		422	50	47.5	50	20.0	50
2	LowVoltageEB	Square Butt With Backing		422	50	47.5	50	20.0	50
3	GTAW	V Groove Butt With Reinforced Shou		402	50	25.0	50	22.5	50
4	GTAW	V Groove Butt With Backing		402	50	25.0	50	22.5	50
5	HighVoltageEB	V Groove Butt With Backing		369	50	47.5	0.5	16.0	50
6	Upset	Square Butt Joint		437	Failed	47.5	50	40.0	50
7	Inertia	Square Butt Joint		420	Failed	47.5	50	40.0	50
8	ContinuousDrive	Square Butt Joint		420	Failed	47.5	50	40.0	50
9	LowVoltageEB	Square Butt With One Relief Notch A		417	50	47.5	50	20.0	50
10	LowVoltageEB	Square Butt Joint		417	50	47.5	50	20.0	50
11	HighVoltageEB	Square Butt With One Relief Notch A		417	50	47.5	50	20.0	50
12	LowVoltageEB	Square Butt With Relief Notches And		417	50	47.5	50	20.0	50
13	HighVoltageEB	Square Butt With Relief Notches And		417	50	47.5	50	20.0	50
14	LowVoltageEB	Square Butt With One Relief Notche		417	50	47.5	50	20.0	50
15	LowVoltageEB	Square Butt With Relief Notches		417	50	47.5	50	20.0	50
16									

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Figure 23. The table of results for "Cap B" to "Body B".

Analysis

The composition of the materials used for "Body B" and "Cap B" have good to excellent weldability. The addition of filler metal to improve weldability is not required for these two material compositions. Again, GTAW needs to be grooved for penetration requirements. We chose weld scenario 1 (Figure 23), a High Voltage Electron Beam with backing.

Weld 11: Final Closure - "Body A" to "Body B"

The final closure weld, "Body A" to "Body B", is modeled in SmartWeld as a hemisphere to a plate. The thickness of the hemisphere is .190" and the thickness of the plate is .500" (see Figure 24) with the function of the weld being Structural. Again, both piece parts are made of 304L stainless steel.

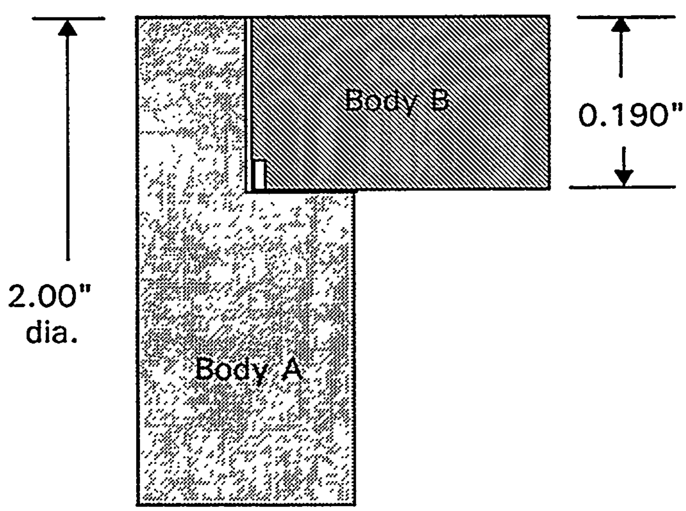


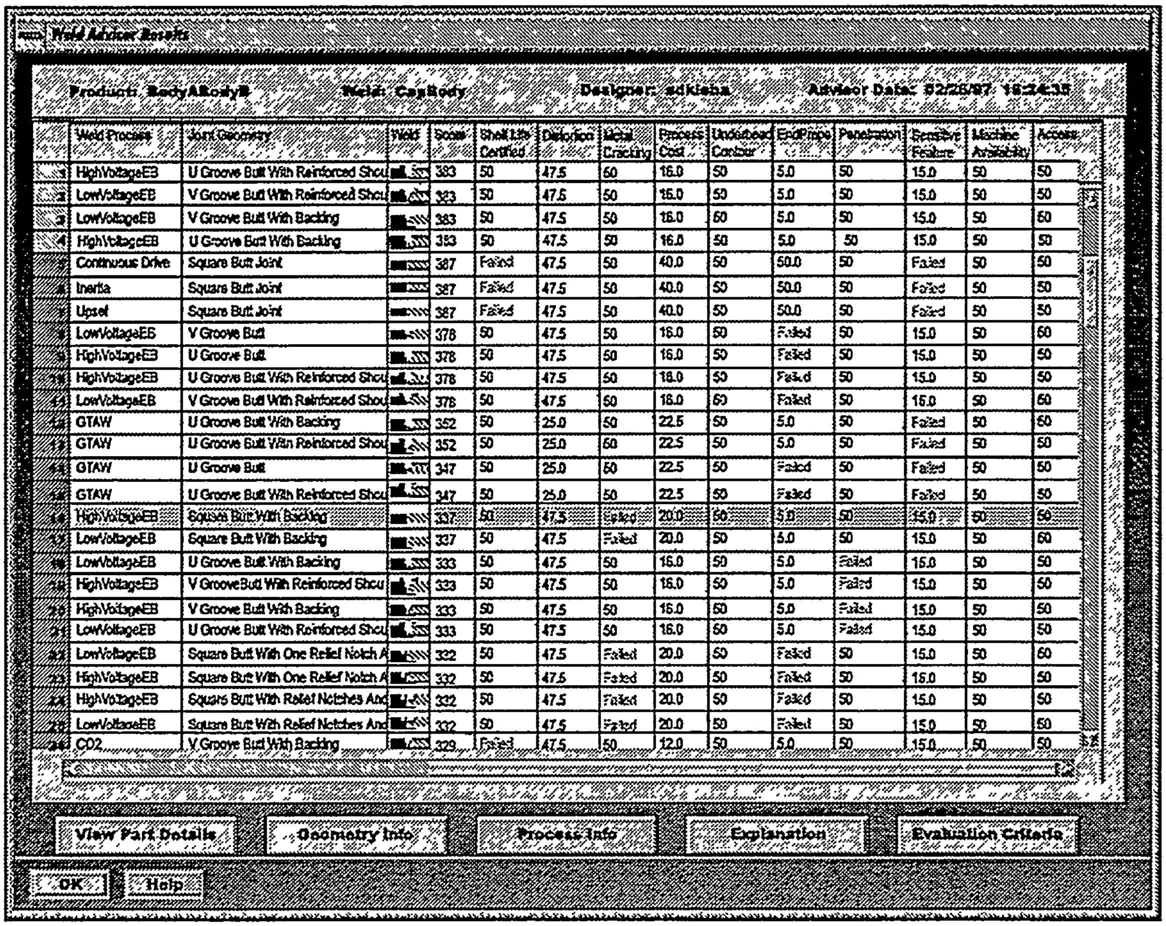
Figure 24. The final closure weld, "Body A" to "Body B."

The answers to the "Weld Specific Requirements" were:

a) Welding Site:	Any		
b) Heat/Stress Sensitive feature Nearby:	Yes		
c) Sensitive feature distance from weld:	.120"		
d) Heatsink Allowed:	None		
e) Access:	One Side		
f) Service Environment:	Embrittling		
g) Service Loading:	Static		
h) Distortion Concern - Shrinkage:	Normal		
i) Distortion Concern - Warpage:	Normal		
Material Chemistry - Body A:	Cr/Ni Equiv. Ratio	=	1.51
	Ferrite Number	=	1.71

- Body B:	Weldability	= Medium
	Cr/Ni Equiv. Ratio	= 1.64
	Ferrite Number	= 5.56
	Weldability	= Good
h) Certified Shelf Life Required:	Yes	

The table of results from the Welding Advisor is shown in Figure 25.



	Weld Process	Joint Geometry	Weld	Score	Shelf Life Certified	Distortion	Metal Cracking	Process Cost	Underbead Contour	EndPipe	Penetration	Sensitive Feature	Machine Availability	Access
1	HighVoltageEB	U Groove Butt With Reinforced Shou		383	50	47.5	60	16.0	50	5.0	50	15.0	50	50
2	LowVoltageEB	V Groove Butt With Reinforced Shou		383	50	47.5	50	16.0	50	5.0	50	15.0	50	50
3	LowVoltageEB	V Groove Butt With Backing		383	50	47.5	50	16.0	60	5.0	50	15.0	50	60
4	HighVoltageEB	U Groove Butt With Backing		383	50	47.5	50	16.0	50	5.0	50	15.0	50	50
5	Continuous Drive	Square Butt Joint		387	Failed	47.5	50	40.0	50	50.0	50	Failed	50	50
6	Inertia	Square Butt Joint		387	Failed	47.5	50	40.0	50	50.0	50	Failed	50	50
7	Upset	Square Butt Joint		387	Failed	47.5	50	40.0	50	50.0	50	Failed	50	50
8	LowVoltageEB	V Groove Butt		378	50	47.5	50	16.0	50	Failed	50	15.0	50	60
9	HighVoltageEB	U Groove Butt		378	50	47.5	50	16.0	50	Failed	50	15.0	50	50
10	HighVoltageEB	U Groove Butt With Reinforced Shou		378	50	47.5	50	18.0	50	Failed	50	15.0	50	50
11	LowVoltageEB	V Groove Butt With Reinforced Shou		378	50	47.5	50	18.0	60	Failed	50	16.0	50	60
12	GTAW	U Groove Butt With Backing		352	50	25.0	50	22.5	50	5.0	50	Failed	50	60
13	GTAW	U Groove Butt With Reinforced Shou		352	50	25.0	60	22.5	50	5.0	50	Failed	50	50
14	GTAW	U Groove Butt		347	50	25.0	50	22.5	50	Failed	50	Failed	50	50
15	GTAW	U Groove Butt With Reinforced Shou		347	50	25.0	50	22.5	50	Failed	50	Failed	50	50
16	HighVoltageEB	Square Butt With Backing		337	50	47.5	Failed	20.0	60	5.0	50	15.0	50	50
17	LowVoltageEB	Square Butt With Backing		337	50	47.5	Failed	20.0	50	5.0	50	15.0	50	60
18	LowVoltageEB	U Groove Butt With Backing		333	50	47.5	50	16.0	50	5.0	Failed	15.0	50	50
19	HighVoltageEB	V Groove Butt With Reinforced Shou		333	50	47.5	50	16.0	50	5.0	Failed	15.0	50	50
20	HighVoltageEB	V Groove Butt With Backing		333	50	47.5	50	16.0	60	5.0	Failed	15.0	50	50
21	LowVoltageEB	U Groove Butt With Reinforced Shou		333	50	47.5	50	16.0	60	5.0	Failed	15.0	50	50
22	LowVoltageEB	Square Butt With One Relief Notch A		332	50	47.5	Failed	20.0	50	Failed	50	15.0	50	60
23	HighVoltageEB	Square Butt With One Relief Notch A		332	50	47.5	Failed	20.0	50	Failed	50	15.0	50	50
24	HighVoltageEB	Square Butt With Relief Notches And		332	50	47.5	Failed	20.0	50	Failed	50	15.0	50	50
25	LowVoltageEB	Square Butt With Relief Notches And		332	50	47.5	Failed	20.0	50	Failed	50	15.0	50	50
26	CO2	V Groove Butt With Backing		329	Failed	47.5	50	12.0	50	5.0	50	15.0	50	50

Figure 25. The results from the Welding Advisor for the final closure weld, "Body A" to "Body B."

Analysis

The weldability of the two components joined in the closure weld are quite different. Body A has poor weldability as reflected in the low Cr/Ni equivalency ratio and low ferrite number. Body B has good weldability values for ferrite and Cr/Ni equivalency ratio. The welding advisor makes suggestions based on the worst case conditions when two materials of different weldability are to be joined. The electron beam process is recommended because of the heat sensitive feature close to the weld, the groove because of the need for filler to reduce cracking and finally the U groove for High Voltage Electron Beam because of underbead contour requirements for structural welds. The Welding Advisor should have scored welds 3 and 4 higher than 1 and 2 since materials of two different thickness are being joined and backing is preferred to an open root weld. The backing also helps the fixturing and alignment. No heat sinking was possible in this case.

We selected an electron beam process with a square groove and backing bar for this weld. It was ranked as 16^{th} by the advisor and failed the weld cracking test (see figure 25). This selection of process and joint geometry was driven by process availability (Electron Beam cold wire feed was not available) and the mixing of the body B material will improve the weldability.

Summary

The welding experts involved in this analysis agreed with the recommendations and advice given by the Welding Advisor in all eleven welds. They did not, however, use the weld configurations as recommended by the Welding Advisor in all eleven welds. The agreement between the Welding Advisor and the Production welds are summarized in Table 3.

Table 3. Summary of agreement between the Welding Advisor and production weld.

Weld Number	Piece Parts	Expert Agreed	Used in Production	Notes
1	Tube / Body A	yes	yes	joint design was modified for production
2	Tube / Body A	yes	yes	joint design was modified for production
3	Plug / Body B	yes	yes	
4	Plug / Body B	yes	yes	
5	Stem / Body A	yes	yes	
6	Stem / Body B	yes	yes	
7	Disk / Body B	yes	yes	
8	Plunger / Body A	yes	no	proven production history; specifics of weld
9	Cap A / Body A	yes	no	proven production history
10	Cap B / Body B	yes	yes	
11	Body A / Body B	yes	no	process availability; weldability improved by mixing

Note that extra caution was applied to all fusion welds involving "Body A". This is because of the poor weldability of "Body A" (weldability is not a factor in solid state welds like weld 5). The use of instock forged material for "Body A" is a design requirement because new stock would require at least two years to acquire.

To summarize, this first use of SmartWeld on a real system that is currently in design was a success. The Welding Advisor is quite sophisticated and the first time user should get training or assistance from a knowledgeable user. The system is designed to support most routine welding problems in a thorough and complete manner with difficult configurations and situations reserved for the welding experts. Some assumptions made by the Advisor were confusing, for example, for tube attachments, access from one side assumes the access was from the outside which was not the case for the CSD tube weld. Not only did the welding advisor concur with most of the planned weld configurations, but it discovered potential problems with the welds involving "Body A". The suggestions have already been acted upon in that one weld geometry was modified and experiments on the others have commenced. This translates directly into schedule and budget savings by discovering the potential problems early in development and not during TMS or production. Those cases where the Advisor's recommendations were not followed were based on favorable experience or information not supplied to the advisor. In all cases, the joints and processes recommended by the advisor were the most risk free, and the best choices for a large production build.

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